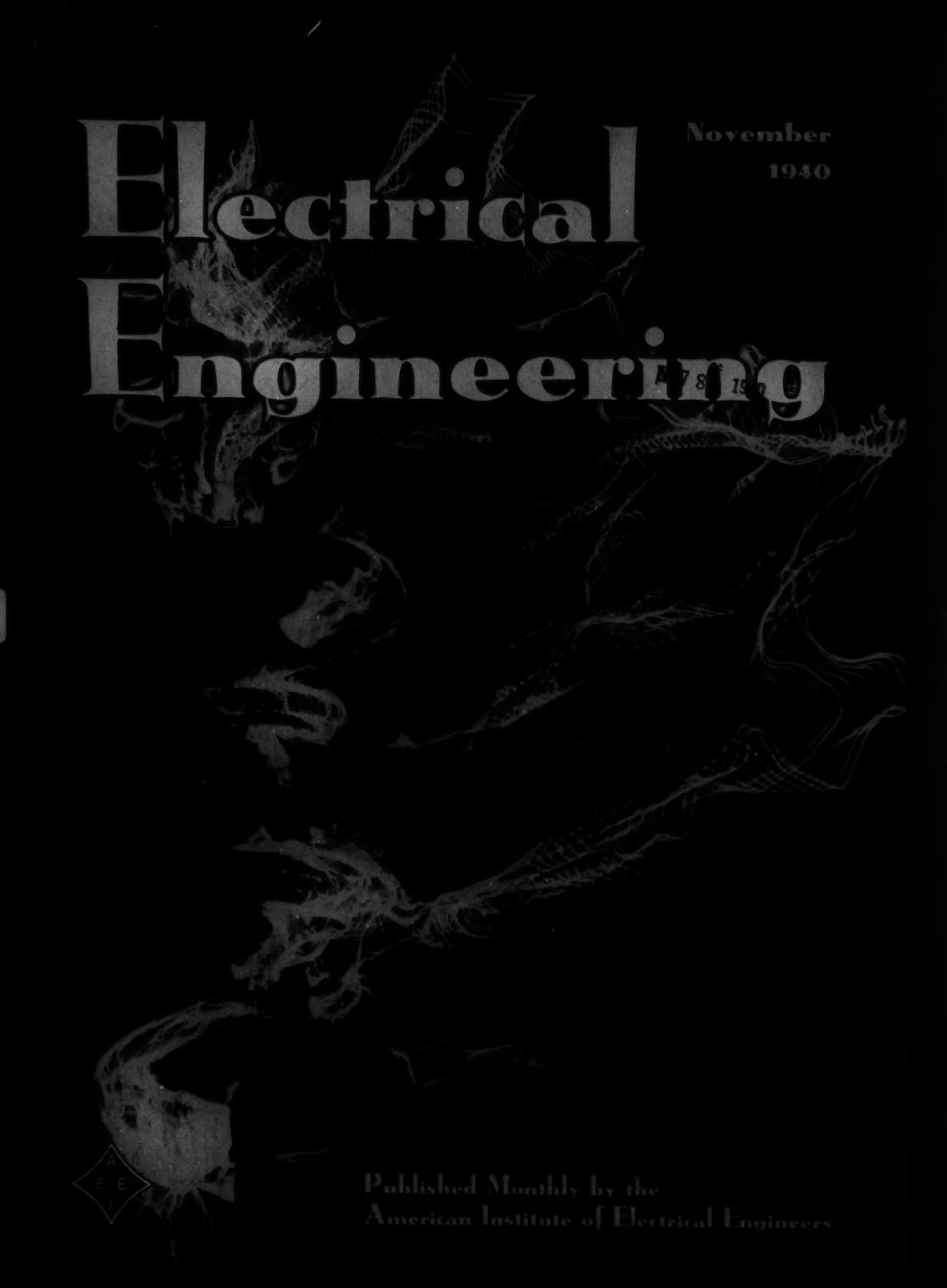
Electrical Engineering

November
1940



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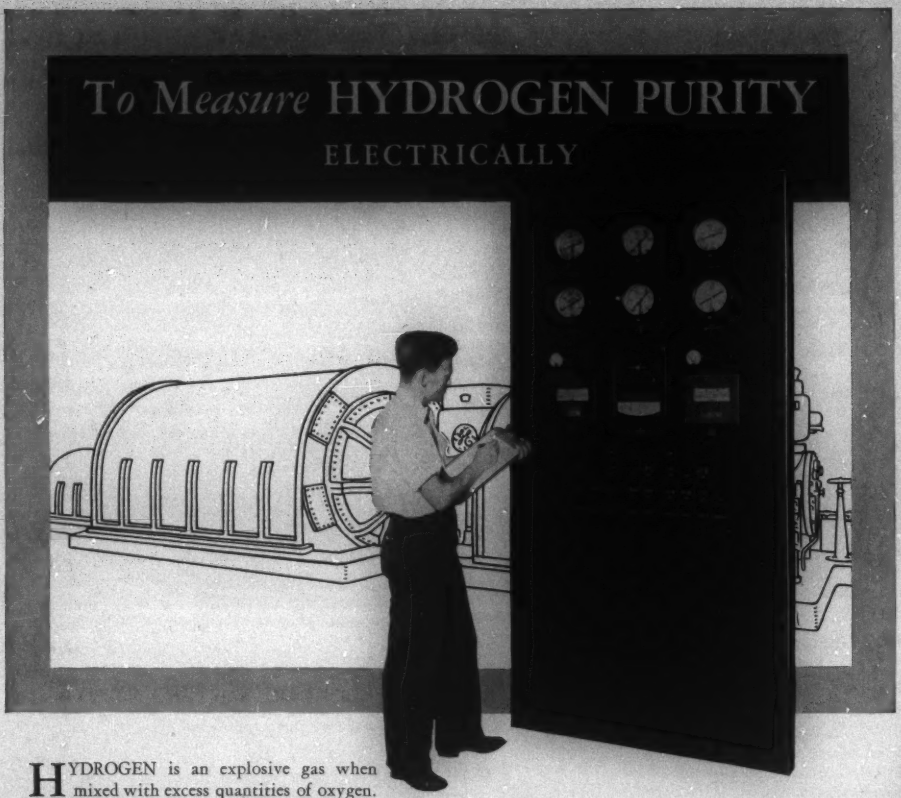
To Measure HYDROGEN PURITY ELECTRICALLY



HYDROGEN is an explosive gas when mixed with excess quantities of oxygen. Therefore, when filling hydrogen-cooled turbine-generators, converters, and condensers, it is necessary to know the hydrogen concentration at all times.

To fill the casing, carbon dioxide is pumped in, and air is let out until the percentage of carbon dioxide in air is about 70 per cent. Hydrogen is then admitted until the percentage of hydrogen in carbon dioxide is about 97 per cent. A somewhat similar reverse procedure is used to empty the casing.

This operation requires a means of measuring the various gas mixtures in order to prevent the formation of an explosive mixture. The changing analysis of the gas must be known throughout the operation, and particularly at the changeover points, so that safety of the procedure is assured. This requires an indicating instrument, for chemical analysis is too slow, as well as too expensive.

An electric instrument, operating on the thermal-conductivity principle, was developed by G-E engineers for this purpose. In addition to giving a continuous analysis, it indicates the purity of the hydrogen after the casing is filled, and while the machine is in operation. By means of an alarm system, it gives both visible and audible warnings, should the hydrogen mixture drop below a predetermined percentage.

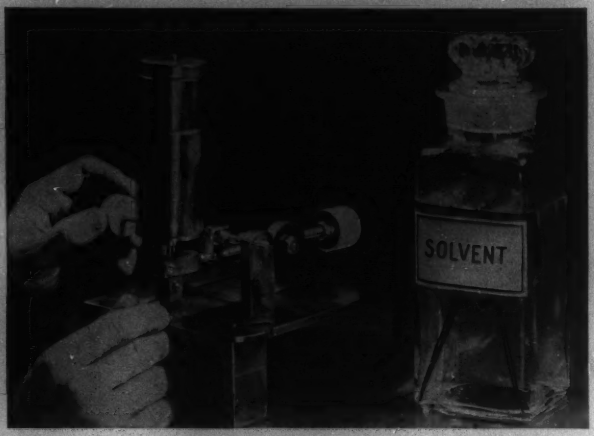
In addition to building instruments for special measurement problems, G.E. offers a complete line of standard instruments for the measurement of any electrical quantity—current, voltage, resistance, watts—in styles and ratings to fill every need. When you have a problem that involves measurement, let us help you solve it. General Electric Company, Schenectady, N. Y.

HEADQUARTERS FOR ELECTRICAL MEASUREMENT

GENERAL ELECTRIC

Don't guess! . . . Use these enameled wire tests and know if your wire has *Balanced* insulation

THE SOLVENT-RESISTANCE TEST is one of several tests which measure the Balanced Quality of enameled wire insulations



The solvent-resistance test applies an adjustable scraping load on the enamel film after immersion in solvent solution

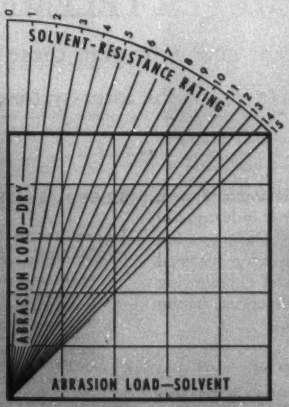
HOW THE SOLVENT-RESISTANCE TEST DETECTS POOR INSULATION

A solvent-resistance test measures the resistance of an enamel film to the action of solvents.

The Belden Solvent-Resistance Tester is a standard test instrument, perfected by Belden engineers, for applying an adjustable scraping load to the surface of a slow-moving specimen of enameled wire after it has been immersed for a definite period in a solvent.

By comparing the load required to scrape the film after immersion with the load required before immersion, the effect of the solvent is accurately determined. Unless the ratio of the two readings is above a certain percentage, the enameled wire is rejected, because it indicates that the enamel cannot resist the action of solvents. Only "balanced" insulation will survive this test.

Close-up of Abrasion Tester



A crucial test of enameled wire is its ability to resist specific solvents . . . . . In a Balanced insulation this characteristic must rate high, or else the other valuable characteristics of the insulating film are of no value.

• • •

WHAT IS BALANCED INSULATION?

Balanced insulation is an enamel film which offers a "balanced" combination of qualities.

For example, in the matter of solvent-resistance, it is essential for the enamel film to resist specific solvents. But it also is essential for the film to be flexible. And, in addition to flexibility the film must survive mechanical abrasion in winding machines. Finally, it must be uniform in thickness and have good aging characteristics. When all these qualities are combined in one insulating film we have "balanced insulation."

In Beldenamel, all these qualities are carefully balanced for the best performance of the wire in your winding department and in the finished product. You get the lowest OVER-ALL winding costs because no characteristic is sacrificed. The evenly balanced qualities make Beldenamel the ideal enameled wire for all types of windings and service.

Do you want to know if you are using wire with balanced insulation? Just adopt Belden standard test methods . . . and you will have a constant check on your magnet wire insulation. Belden tests eliminate guesswork in wire-buying. Every characteristic is tested separately and accurately rated.

Belden

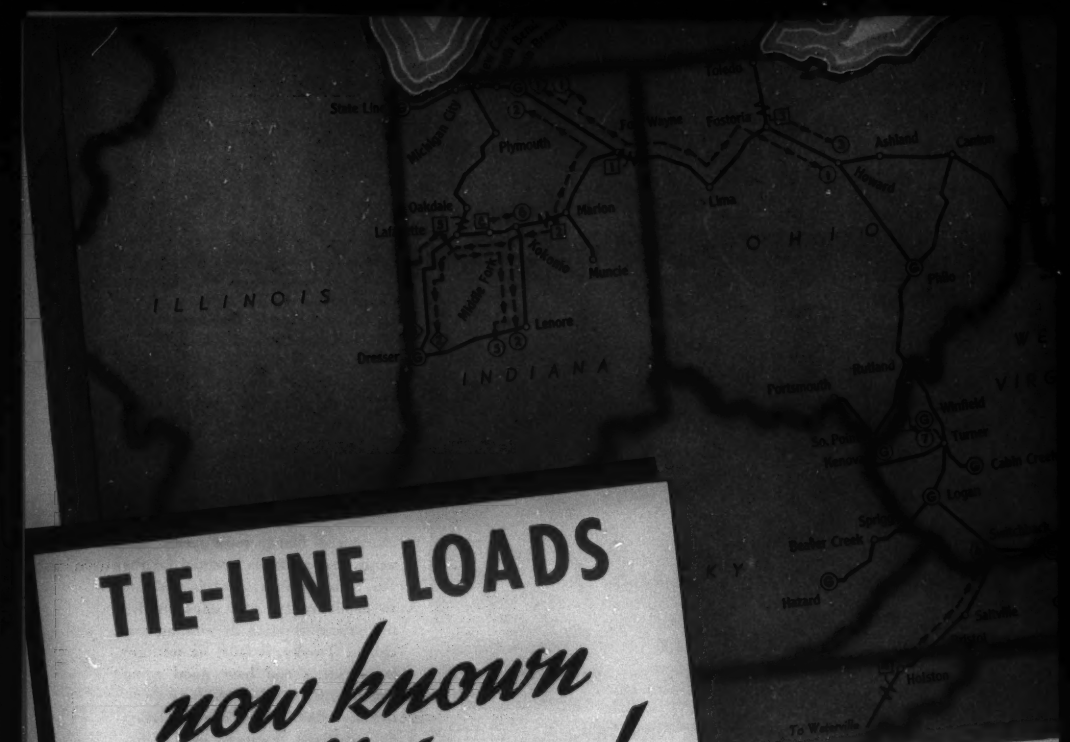
MANUFACTURING COMPANY

4835 W. Van Buren St., Chicago

Manufacturers of

Beldenamel • Silkenamel • Cotenamel
Glaze-enamel • Calenamel and Formvar

Further data on tests and instruments for rating characteristics of *Balanced* insulation sent on request.



TIE-LINE LOADS *now known at all times!*

Continuous chart records, furnished by

BRISTOL'S METAMETER TELEMETERING SYSTEM

operating over carrier current channels, give these several neighboring electric companies accurate visual pictures of the inter-system tie-line loads every moment of the day and night!

Of the several ways in which Bristol's Metameter System of Telemetering is now serving the electric industry, one of the most important is in helping the central station load dispatcher continually and correctly keep informed of the tie-line loads between his own and neighboring companies. The several installations described herein are interesting applications of this kind.

BRISTOL'S METAMETER SYSTEM (1) *See map*

Transmitter at Fort Wayne, Ind. — Measures tie-line power interchange between Ohio Power Co. and Indiana & Michigan Electric Co.

And transmits readings via carrier channel to:

Recording Receiver at Twin Branch, Ind., in dispatcher's office of Indiana & Michigan Electric Co.

Receiver for load control at Twin Branch, Ind., in generating station of Indiana & Michigan Electric Co.

Recording Receiver at Howard, Ohio, in dispatcher's office of Ohio Power Co.

BRISTOL'S METAMETER SYSTEM (2) *See map*

Transmitter at Marion, Ind. — Measures tie-line power interchange between Indiana & Michigan Electric Co. and Northern Indiana Power Company.

And transmits readings via carrier channel to:

Recording Receiver at Twin Branch, Ind., in dispatcher's office of Indiana & Michigan Electric Co.

Recording Receiver at Lenore, Ind., in dispatcher's office of Northern Indiana Power Company.

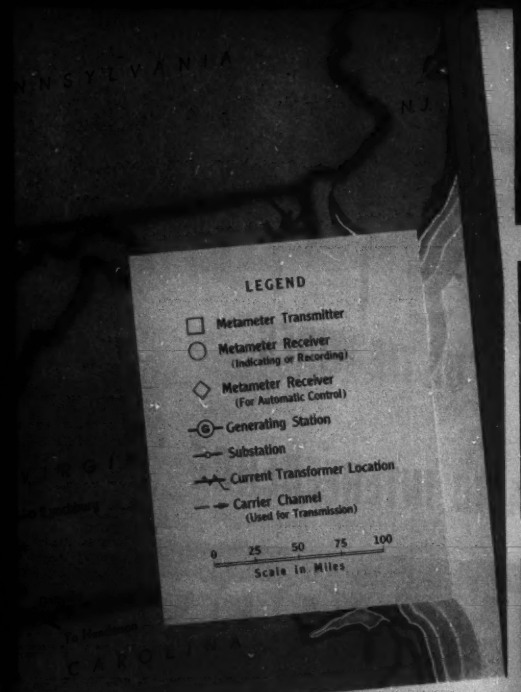
Receiver for load control at Dresser, Ind., in generating station of Northern Indiana Power Company.

BRISTOL'S METAMETER SYSTEM (3) *See map*

Transmitter at Fostoria, Ohio — Measures tie-line power interchange between Ohio Power Co. and Toledo Edison Co.

And transmits readings via carrier channel to:

Recording Receiver at Howard, Ohio, in dispatcher's office of Ohio Power Co.



BRISTOL'S METAMETER SYSTEM (4) *See map*

Transmitter at Holston, Tenn. — Measures tie-line power interchange between Carolina Power & Light Co. and Appalachian Electric Power Co.

And transmits readings via carrier channel to:

Recording Receiver at Switchback, West Va., substation of Appalachian Electric Power Co.

BRISTOL'S METAMETER SYSTEM (5) *See map*

Transmitter at Lafayette, Ind. — Measures tie-line power interchange between Public Service Co. of Indiana and Northern Indiana Public Service Co.

And transmits readings via carrier channel to:

Recording Receiver at Lenore, Ind., in dispatcher's office of Public Service Co. of Indiana.

Receiver for load control at Dresser, Ind., in generating station of Public Service Co. of Indiana.

Note: In addition to the Metameter Systems listed above, there are two other interesting Metameter installations in the area covered by the map, as follows:

BRISTOL'S METAMETER SYSTEM (6) *See map*

Two Transmitters are installed in the unattended substation of the Northern Indiana Power Co. at Middle Fork, Ind. The receivers are located in the substation at Kokomo, Ind. One transmitter measures the tie-line power interchange at Middle Fork between the Northern Indiana Power Co. and the Public Service Co. of Indiana; while the other measures voltages of the 33-KV line of the Northern Indiana Power Co. Readings as selected are obtained over a 20 mile power line carrier system used in connection with automatic supervisory control equipment.

BRISTOL'S METAMETER SYSTEM (7) *See map*

Thirteen Transmitters transmit readings of kilowatt hours, kilowatts, kilovars, voltage, gate position, and head and tail water levels over a 17 mile power line carrier system used in connection with automatic supervisory control equipment, from the Winfield, W. Va., hydro-generating station of the Kanawha Valley Power Co. to indicating receivers located in the Turner, W. Va., substation.

THE BRISTOL COMPANY, WATERBURY, CONNECTICUT
Branch Offices in Principal Cities

***METAMETER is a system of remote measurement and control made exclusively by The Bristol Company.**

Close-up of the Metameter Transmitter at Marion, Ind.

Metameter Transmitter at Fort Wayne, Ind.

View showing the two recording Receivers at Twin Branch, Ind. The one at the left operates from the Transmitter at Fort Wayne, Ind.; the one at the right from the Transmitter at Marion, Ind.

Another view of the Metameter Recording Receivers in the dispatcher's office of the Indiana & Michigan Electric Co. at Twin Branch, Ind.

INFORMATION CONTINUALLY SUPPLIED BY BRISTOL'S METAMETER

FOR LOAD DISPATCHER OF CENTRAL STATION SYSTEM

1. Load (active and reactive power and power demand) in each tie-line interconnecting system with neighboring system
2. Output, or total generated power, of each generating station
3. Total output of all generating stations, on a single instrument
4. Active and reactive power and power demand at key points on important transmission circuits
5. Water level and waterwheel gate position in hydroelectric plant

FOR OPERATOR OF GENERATING STATION

1. Total output generated in system
2. Output of each associated attended or unattended generating station in system
3. Desired output of operator's own station

OTHER SERVICES PERFORMED BY BRISTOL'S METAMETER

ADJUNCT TO AUTOMATIC REGULATION OF GENERATING STATION OUTPUT FOR

1. Holding tie-line power or power demand within the desired limits
2. Introducing a tie-line load continuous bias into the automatic frequency controller
3. Providing automatic adjustment of load between stations, and even between individual generators in the same station

AUTOMATIC CONTROL OF INDUCTION OR STEP VOLTAGE REGULATORS

1. Holding power or power demand in one of several interconnections within desired limits
2. Holding the power flow in a loop transmission circuit within the desired limits

WRITE!

For a complete discussion of how the Metameter can serve in improving central station operations write for Bulletins 515 and 530

They're a positive cure for insulator radio noise—O-B Clamptops—and the several ways they effect savings all help pay for the solution of your radio problem. Eliminating costly radio interference is one way they save. Using a clamp to hold the conductor, they prevent conductor wear from tie wire rubbing—another way they save. Overcoming release of conductors from bad tie wires is a third way. And making hot-line work easier is a fourth. To save money while radio-proofing lines, simply install O-B's modern pintypes—the Clamptops.

Ohio Brass (B)

MANSFIELD, OHIO, U. S. A.

Canadian Ohio Brass Co., Ltd., Niagara Falls, Ont., Canada

★ ★

Electrical Engineering

Registered U. S. Patent Office

for November 1940—

The Cover: A standard 60-cycle AIEE wet flashover test on a six-unit string of suspension insulators, as seen by the camera.

Photo courtesy Ohio Brass Company

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¶ Correspondence is invited on all controversial matters.

High Lights • •

Branch Prize Papers. The AIEE national prize for Branch paper, for student papers presented during the year ending June 30, 1939, was awarded jointly to authors of two papers, and was presented to the recipients at the Institute's 1940 summer convention; abstracts of both papers appear in this issue. One paper describes a new electronic relay for initiating arc discharges in gases, which was developed primarily for starting low-voltage fluorescent lamps and is already being used commercially for that purpose (*page 461*). The other paper describes a method of improving the acoustical response of an audio-frequency sound system by frequency-selective feedback (*pages 460–1*).

Frequency Modulation. Radio communication is made possible by varying one of the characteristics of a high-frequency electromagnetic wave in accordance with the instantaneous variations of the signal to be transmitted; this process is known as modulation. Variation of the amplitude of the wave has been the accepted method, but frequency modulation, in which the amplitude remains constant and the frequency varies, offers unique advantages and may produce a marked change in broadcasting in the next few years (*Transactions pages 613–25*).

High-Intensity Mercury Lamps. As early as 1906, the characteristics of the mercury arc under pressures higher than atmospheric pressure were investigated. Commercial development of practical high-intensity mercury-arc lamps operating at high pressures was delayed, however, because suitable materials for manufacturing practical lamps were lacking. New materials developed in recent years now have brought these lamps out of the laboratory, and further developments are expected to extend their applications (*pages 444–7*).

Ceramic Insulation. Defined as "materials that are inorganic and brought to permanent shape and hardness by high temperatures," ceramic materials occupy an almost indispensable position in electrical apparatus and circuits. An authority on the subject reviews in this issue the various types of ceramic materials used for electrical insulation, the raw materials used in their manufacture, methods of manufacture, and characteristics and applications of the finished products (*pages 451–9*).

High-Speed Motion Pictures. In order correctly to design apparatus to meet the demands of the modern age, involving high power, high speed, and complicated mechanical movement, it is necessary to be able to analyze mechanical motion with great precision. High-speed motion pictures have proved their value for this purpose; a camera recently developed, using a continuously moving film, is capable of taking pictures at a rate of 4,000 per second (*pages 448–50*).

Differential Relay. High-speed differential relaying for generator protection is complicated by the presence of the d-c transient in asymmetrical through fault currents, which produces a false differential current because of dissimilar performance of the current transformers. Means have been provided in a new relay to discriminate between false and true differential currents of tripping magnitude (*Transactions pages 608–12*).

Transient Stability. An extension of the graphical equal-area method of determining transient stability of power systems, applicable to systems that can be reduced to two equivalent machines, gives the angular position of the synchronous machine as a function of time, and thereby permits the general method of the equal-area solution to be applied to system disturbances in which time is a factor (*pages 462–5*).

Loading Transformers. Additional capacity may be obtained by the method of loading transformers by temperature, but consideration must be given to the effects of different shapes of system load factors on aging of insulation. Permissible peak loads will vary depending on ambient temperature and load factor, for which loading curves have been plotted (*Transactions pages 632–6*).

Electron Microscope. Having a resolution capability at least 20 times better than the theoretical limit of the ordinary microscope, the electron microscope in its present form provides the research worker with "an opportunity unparalleled since the original discovery of the compound microscope." Continued research is expected to lead to instruments of yet greater power and usefulness (*pages 441–3*).

Conductance of Insulating Oils. Apparatus has been developed for measuring at low voltages the d-c conductances of electrical-insulating oils. Measurements of the d-c conductance with time of a highly refined oil substantiate the theory that low voltage methods do measure the true d-c conductance of electrical insulating oils (*Transactions pages 625–8*).

Technical Conferences. Four technical conferences held at AIEE meetings are reported in this issue: two conferences on load swings, one held at the 1940 summer convention and one at the Pacific Coast convention (*pages 468–9*); and two conferences held at the recent Cincinnati meeting, one on motors and one on protective lighting (*pages 467–8*).

Induction-Motor Starting Torques. When starting an induction motor, transient alternating torques occur having the same frequency as that of the power supply. Analysis and tests show that for the first few cycles these torques may be several times the pull-out torque (*Transactions pages 603–07*).

Dead Points. Certain squirrel-cage motors may have a wide variation in starting torque depending on the angular position of the rotor. A new analysis, confirmed by test results, makes possible correlation of many apparently divergent results and avoidance of troublesome combinations in design (*Transactions pages 637–42*).

A-C Bridge. A new rapid automatic recording a-c bridge continuously records the power factor and capacitance during life runs or short-time tests on cables, capacitors, and insulating materials at a frequency of 60 cycles per second (*Transactions pages 628–31*).

Cincinnati Meeting. With a registered attendance of 599, the AIEE Middle Eastern District meeting recently concluded at Cincinnati, Ohio, established a new attendance record for that District (*pages 466–7*).

Publication Procedure. Some of the changes in publication procedure brought about by the recently adopted changes in AIEE publication policy are explained in this issue (*page 469*).

Coming Soon. Among special articles and technical papers currently in preparation for early publication are: an article on modern network radiobroadcasting by C. A. Rackey; an article reporting experimental data on electric shock by C. F. Dalziel (M'39); an article on the use of infrared lamps for industrial heating purposes by P. H. Goodell (A'40); an article outlining how the instrument landing of aircraft is accomplished; a paper on reference values for temperature, pressure, and humidity by P. L. Bellaschi (F'40) and P. H. McAuley (A'36); a paper on rating of potential devices and suggested material for a standard by J. B. Clem (F'38) and P. O. Langguth (A'28); a paper describing a new high-speed thermal wattmeter by J. H. Miller (M'26); a paper describing a method for detecting the ionization point on electrical apparatus by G. E. Quinn (M'33); a paper on computation of accuracy of current transformers by A. T. Sinks (A'36); a paper on the dielectric strength and life of impregnated-paper insulation by J. B. Whitehead (F'12); two papers on a decade of progress in electronics in the field of communication and in fields other than communication by S. B. Ingram (M'38) and W. C. White (M'30); a paper on an oilless circuit interrupter using water by W. M. Leeds (M'38); and a paper describing measurements at radio frequencies by H. R. Mealh (A'37), P. C. Michel, M. W. Scheldorf (A'38), and T. M. Dickinson.

Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶Address changes must be received by the 15th of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). Copyright 1940 by the American Institute of Electrical Engineers. Printed in the United States of America.
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Electrons Extend the Range

V. K. ZWORYKIN
MEMBER AIEE

The recently developed electron microscope has a resolution capability at least 20 times greater than that of the ordinary microscope, and research aimed at extending its range is still in progress. The importance of this new tool to biology and medicine would be hard to overestimate; industry also expects to find many uses for it.

"SEEING is believing," an old adage tells us and indeed man owes his knowledge of the world about him primarily to his sense of sight. Shape, brightness, color—these suffice to identify most familiar objects. Yet, however marvelous an instrument the human eye may be, its ability to recognize and differentiate is limited. Two objects so close together that their images are projected by the lens of the eye on the same sensitive nerve cell of the retina cannot possibly be told apart. Thus, a set of halftone dots or shading lines separated by less than 1/100 inch appears to the average eye as a uniform gray surface without structure—the dots or lines of the object are not "resolved" by the eye, whose "limit of resolution" lies in the neighborhood of 1/100 inch.

To make it possible for the eye to resolve finer details in an object, it is necessary to project a larger image thereof on the retina than can be formed by the lens of the eye by itself. This may be accomplished by placing a convex lens between the object and the eye. If still higher resolution is demanded, the simple magnifier must be replaced by a compound microscope. Here a first lens, the objective, produces a greatly enlarged image of the object, which image is then viewed with the aid of a suitable magnifier, the eyepiece. As an alternative, the eyepiece may act as a projection lens and record the image observed on a photographic plate.

The discovery of the compound microscope by Leeuwenhoek during the latter part of the 17th century opened up a whole new world to the scientifically curious. From the primitive life of the ponds to the cell structures of the higher plants and animals, nature had to yield up more and more of her secrets as, in the past three centuries, this powerful instrument was improved and perfected. But with this perfection came the recognition of a barrier which could not be surmounted. Light, the medium producing the enlarged image, could not resolve details appreciably smaller than its own wave length. As the latter is of the order of 2/100,000 inch, it followed that structures less than about 1/100,000 inch apart could not be separated; increasing the magnification beyond 1,000 or 2,000 diameters yielded a larger but not more informative picture. All details simply appeared progressively more blurred.

The obvious remedy for this limitation of the microscope was the use of a finer-grained medium, having shorter wave lengths. Thus, in some instruments, ultraviolet radiation has replaced visible light. However, only a relatively small improvement, by a factor of the order of two, could be thus obtained, as the far ultraviolet is too readily absorbed by the lenses to be applicable. X rays, also, do not lend themselves to this task because of the difficulty of refracting and reflecting them. Thus, for a number of decades, it appeared as though, to all intents and purposes, the ultimate limit in the direct observation of minute objects had been reached.

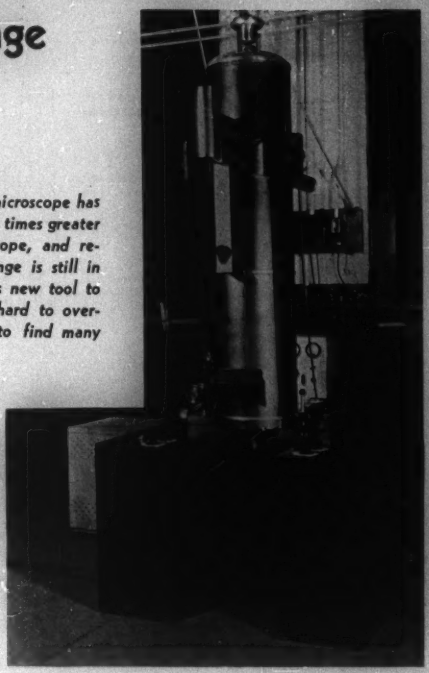

Figure 1. The RCA electron microscope

The situation was changed radically with the advent of the electron microscope. In 1924 the French physicist Louis de Broglie had indicated that a stream of electrons should have wave properties similar to those of a beam of hard X rays, the wave length being inversely proportional to the electron velocity. For electrons having a velocity corresponding to 30 to 100 kv, this wave length is approximately 1/100,000 of the wave length of visible light. Two years later Heinrich Busch of Darmstadt showed that an axially symmetric electric and magnetic field acted on electron beams just as a lens acted on light beams, bending the paths of the electrons toward or away from the axis. Thus, with the aid of a solenoid or a pair of coaxial apertures at different potentials, an electron source could be imaged sharply on a fluorescent screen or photographic plate.

V. K. ZWORYKIN is associate director, research laboratories, RCA Manufacturing Company, Camden, N. J.

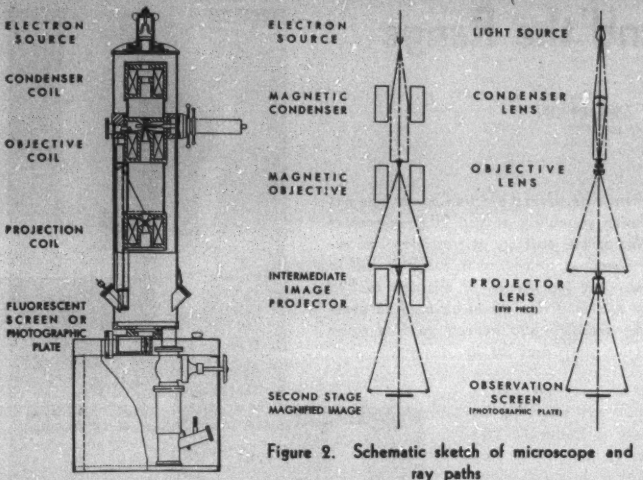

Figure 2. Schematic sketch of microscope and ray paths

Simplified sketch (left) of the electron microscope developed in the RCA laboratories at Camden, N. J. Diagram in center shows how closely the operation of the electron microscope is analogous to that of the conventional light microscope (right). Suitably shaped magnetic fields take the place of glass lenses. A beam of electrons traveling at high velocity (at voltages of from 30 to 100 kv) takes the place of ordinary light. The electron rays are converged by condenser lens onto the specimen. After passing through the specimen, the objective lens coil forms a first image, enlarged about 100 times. The projection lens coil then magnifies the image again about 250 times, making an over-all magnification of 25,000. The final enlarged image can be viewed directly by causing it to strike a fluorescent screen which makes it visible, or it can be made to record the image on a photographic plate for permanent record. The final photograph can be usefully magnified by photographic enlargement up to 100,000 diameters.

Herewith the essential conditions for the creation of an instrument with a resolving power exceeding that of the light microscope by a large factor were fulfilled. However, much further research was required before such apparatus could actually be realized. In this development, particularly that part relating to the production and guiding of the electron beams, the experience gained in the development of earlier electronic devices, such as cathode-ray oscillograph tubes and electronic television tubes, proved of the greatest value. The problem is complicated by the fact that electrons, unlike light, are readily absorbed by any material substance. This requires the evacuation of the interior of the electron microscope and the use of exceedingly thin object supports and specimens. The development of a technique of preparing and mounting biological specimens for examination with electrons was first undertaken by Doctor Ladislaus Marton at the University of Brussels.

In view of their wide experience in connection with electronics and television, it was natural that the RCA laboratories should undertake the development of an electron microscope suitable for research purposes. This work has resulted in the instrument shown in figure 1 and in section in figure 2, designed by Doctor Marton with the co-operation of other staff members. A comparison of the schematic drawings of ray paths in the electron microscope and in a light microscope shows that the operation of the two instruments is essentially similar. The differences are

Figure 3. Typhoid bacillus, magnified 10,000 times

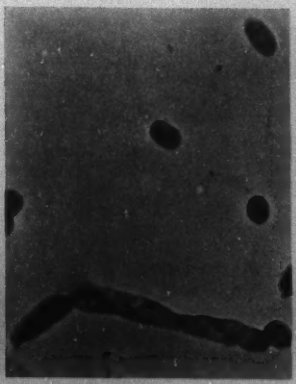

Figure 4. Culture of whooping-cough bacteria, magnified 9,000 times

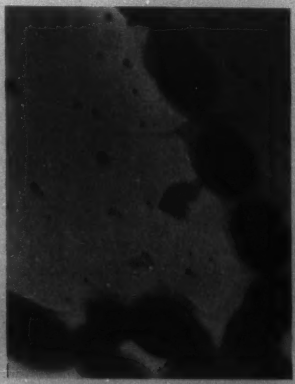

Figure 5. Culture of streptococcus bacteria, magnified 20,000 times

dictated primarily by the differences in the properties of electrons and of light. Electrons leaving the source, a hot tungsten filament, are accelerated to their top speed by the strong electric field between the filament (at a negative potential of 30 to 100 kv) and the anode (at ground potential) placed directly below it. The electron beam issuing from a fine hole in the anode is concentrated on the object by a magnetic condenser lens. Electrons passing through the object and an aperture in the magnetic objective are focused by the latter into an image of the object magnified approximately 100 times and situated just above the magnetic projector lens. This last lens selects a portion of the intermediate image and enlarges it by a factor of approximately 250, yielding a final image projected on an interchangeable fluorescent screen or photographic plate with a magnification of about 25,000. Each of the three lenses consists of a coil of magnet wire enclosed in a soft iron shield so shaped as to concentrate the magnetic field on a short section of the axis of the microscope.

The final image can be observed on the fluorescent screen through vacuum-tight windows in the side of the microscope. A simple periscope arrangement permits the observation of the less highly magnified intermediate image at the same eyelevel, facilitating the selection of the portion of the object to be further magnified. In order to make possible the rapid exchange of objects and photographic plates in spite of the high vacuum existing in the microscope, air locks are provided, similar to the escape chambers of a submarine. For example, when the object has been shifted by an external manipulation to its escape chamber, the latter can be closed off from the rest of the microscope, air can be admitted, and the object exchanged. After the chamber has been pumped out once more, the specimen can be reintroduced into the microscope—an operation that altogether takes only a little more than a minute.

The objects to be examined are deposited on nitrocellulose foils less than 1/1,000,000 of an inch thick. They may be cultures of bacteria, virus filtrates, colloidal suspensions, dusts or smokes, or materials of yet other character. The electron pictures shown in figures 3 to 6, taken by Doctor Marton, give an indication of the possibilities of the instrument. The first shows a typhoid bacillus with its long curved flagella—first revealed in their natural form by the electron microscope. The next picture shows a culture of whooping-cough bacteria, some of the bacteria shown being apparently in various stages of cell division. The large amount of detail visible within the bacteria is particularly worthy of note. Figure 5 reproduces a streptococcus culture. The final picture, figure 6, shows an application of the new microscope to the study of material so finely divided that the light microscope is no longer able to reveal the jagged contours of the individual particles.

A careful examination of pictures such as these shows that the electron microscope has, at the present time, a resolution capability at least 20 times better than the theoretical limit of the ordinary microscope—that is, it can separate objects less than 1/50 of a wave length of visible light or 1/3,000,000 inch apart. Certain fundamental defects of electron lenses, which it has not proved possible to overcome with the means and knowledge now at hand, have so far prevented greatly exceeding this resolution. However, active research in this direction is being carried on and there is every reason to believe that it will lead, in the due course of events, to instruments of yet greater power and usefulness. In the mean time, one thing is certain: The electron microscope in its present form provides the research worker with an opportunity unparalleled since the original discovery of the compound microscope by Leeuwenhoek.

Figure 6. Iron oxide powder (rouge), magnified 15,000 times

Faults in Three-Phase Systems

A PAPER published in the April 1940 issue of the *Bell System Technical Journal*, pages 290–305, presents "A Solution for Faults at Two Locations in Three-Phase Power Systems" and is an outgrowth of studies of double faults to ground in three-phase power systems made by the author, E. F. Vaage (M'39), of the Bell Telephone Laboratories, in connection with work of the Joint Subcommittee on Development and Research, Edison Electric Institute and Bell Telephone System. The paper provides a systematic solution, based upon the method of symmetrical components, by means of which currents and voltages can be determined at times of fault involving any combination of phases at one or two locations on three-phase power systems in which generators may be assumed to be in phase and of the same internal voltage, and where load currents may be neglected.

Trends in High-Intensity Mercury Lamps

GEORGE A. FREEMAN

Although the characteristics of the mercury arc at pressures as high as two atmospheres were investigated more than 30 years ago, lack of suitable materials delayed until recent years the commercial development of practical high-pressure high-intensity mercury-arc lamps.

IN THE decade past, effort in the search for higher-efficiency light sources has been gradually shifting from incandescent-filament lamps to gaseous-discharge lamps. The activity has brought into public use high-intensity mercury lamps for industrial and flood lighting, sodium lamps for highway illumination, and more recently the low-pressure-arc fluorescent lamps for general use. There have been a number of related developments as, for example, the bactericidal Sterilamp and mercury sun lamps.

The fundamental principles of these lamps are not new. There is often a period of many years from scientific discovery to practical use, and so it has been with gaseous discharges. The Cooper Hewitt type of mercury lamp which appeared about 1905 suffered almost no competition from other discharge lamps until the high-intensity mercury lamp had its commercial introduction in the United States in 1934. From a scientific point of view the high-intensity mercury arc was nearly as old as the Cooper Hewitt low-pressure arc. Kuch and Retchinsky in 1906 reported the improved spectral output and high luminous efficiency of mercury arcs at mercury pressures as high as two atmospheres. The 28-year delay in making commercial use of this discovery was due in large part to the lack of materials to make practical lamps. The development of a glass having a softening point of approximately 925 degrees centigrade, and oxide-coated tungsten electrodes for use on alternating current, were the principal factors in giving the high-intensity mercury lamp long life and simplicity.

Similarly, sodium-vapor lamps began their commercial existence in 1932 after a suitable alkali-resistant glass had been developed to resist the corrosive effect of active sodium vapor on the glass envelope. Fluorescent lamps, appearing in 1938, followed the development of efficient fluorescent materials in all colors and suitable starting devices that eliminated the need of high voltage.

The efficiency of a tungsten-filament lamp is definitely limited by the melting point and rate of evaporation of tungsten. Improvements will yet be gained by changing the gas filling to retard tungsten evaporation and by special coiling of the tungsten wire to conserve heat, but at best the gains probably will be slight. Discharge lamps, however, are already two or three times as efficient as tungsten-filament lamps, and their possibilities are not nearly so well explored. The efficiencies of several representative light sources are shown in table I.

Since other workers have already described the development of sodium lamps,[1,2] high-intensity glass mercury lamps,[3–5] and fluorescent lamps[6,7,8] in some detail, it is the purpose here to trace the development of high-intensity mercury lamps in quartz.

From the Cooper Hewitt low-pressure mercury lamp to the type *A-H*1 high-intensity lamp operating with one atmosphere mercury pressure, the gains were increased efficiency, improved color, and more compact design. In furthering these gains, still higher mercury pressures were tried. This meant greater concentration of the arc, resulting in higher heat dissipation per inch of arc length and consequent overtaxing of the materials used in the lamp. The glass envelope was softened by the higher temperature in lamps operating with mercury pressures higher than one atmosphere. Fused quartz was taken as the best material to replace it.

Commercial use of fused quartz, while making possible still more efficient mercury lamps, at the same time presents a new series of problems. Fused quartz of sufficient purity was expensive to manufacture and to use because of its high melting point and low coefficient of thermal expansion. Table II compares these properties with those of other materials. While relatively inert at ordinary temperatures, fused quartz combines readily with alkaline materials at temperatures of 600 degrees centigrade and higher. The use of barium and strontium oxides as the electron-emissive coating in high-pressure quartz lamps therefore was soon found to be poor practice. The extreme conditions imposed upon an electrode by a high-pressure arc sputtered or vaporized the coating over to the quartz envelope. Barium silicate would form, appearing as frosting or crystallization on the quartz inner wall. The sputtering of the electrode must be minimized also

Table I. Efficiencies of Representative Light Sources

Source	Lumens Per Watt
Tungsten 100-watt	16
Tungsten 1,000-watt photoflood (short life)	33
Sodium 10,000-lumen	55*
Daylight fluorescent 30-watt	37*
Green fluorescent 30-watt	75*
Mercury 100-watt type *A-H*4 quartz	35*
Mercury 1,000-watt type *A-H*6 water-cooled quartz	65*
Mercury 400-watt type *A-H*1 glass	40*
Low-pressure mercury Cooper Hewitt	15 to 19

* Efficiency shown is of the lamp proper; over-all efficiency of the lamp and auxiliary equipment is slightly lower.

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Table II. Comparison of the Properties of Quartz With Those of Other Materials

Material	Thermal Coefficient*	Softening Point (Degrees Centigrade)	Strain Point (Degrees Centigrade)
Pure quartz	5.5×10^{-7}	1,667	1,070
96 per cent quartz	7.8	1,442	857
Hard glass for *A-H1* mercury lamps	39	925	679
Pyrex	33	819	510
Nonex	36	756	494
Soft lead glass	87	630	395
Special quartz to tungsten sealing glass	14	1,200	
Tungsten	43	3,370	
Molybdenum	49	2,620	

* Coefficient given is the increase in length per unit length per degree centigrade.

because of the smaller size of the quartz bulb which will darken from sputtered particles sooner than the larger glass bulb that would be used for the same wattage rating. All these problems had to be solved to make practical lamps.

QUARTZ SEALS

A wire of tungsten or of any other metal cannot be sealed directly into quartz to form a gastight seal over a wide range of temperature. As the seal cools after being made, the wire shrinks away from the quartz, which has a lower coefficient of expansion, and leakage results. In low-pressure discharge devices where quartz has been used, seals are made between quartz and metal wires by separating them with several intermediate steps of glasses having graded expansion properties. While satisfactory in many applications, such graded seals have three unsatisfactory features when used in high-pressure mercury lamps. First, their size is necessarily so large as to make large cavities in the arc chamber remote from the arc; second, the softening points of the higher-expansion-coefficient glasses nearest the seal wire are too low for the high concentration of energy; and third, their manufacturing cost is excessive for making economical lamps in quantity.

Any cavity away from the arc may not receive sufficient heat from the arc to vaporize all the mercury, or at least tends to slow up the vaporization and prolong the warming-up period after a lamp is turned on. Typical warming-up characteristics are shown in figure 1 for the 250-watt quartz lamp type *A-H5*. The time for all the mercury to vaporize and maximum light output to be obtained is four or five minutes. A cavity remote from the arc would prolong this time or perhaps prevent normal operation.

The development of a new glass having such properties as to make a single-step quartz-tungsten seal possible has been most important in bringing high-pressure quartz lamps out of the laboratory. The new glass has a high softening point of 1,200 degrees centigrade and a coefficient of thermal expansion of 14×10^{-7}, between those of quartz and tungsten, and the strength to withstand the severe strains in joining these quite different materials. Care is taken in designing the seals to minimize strain by avoiding massive beads or thick regions of glass. Such a design as a press seal used in most lamps and vacuum

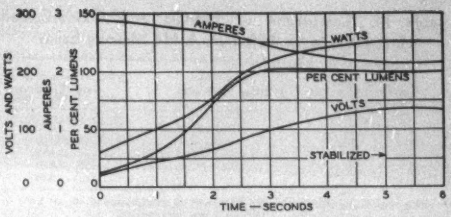

Figure 1. Chart showing heating-up characteristics of type A-H5 250-watt mercury lamp

tubes would not be practical for quartz seals because the strains would be excessive. Figure 2 shows the seal design of the 100-watt lamp.

THORIUM ELECTRODES

The electrode problem has been solved by using non-activated electrodes containing a metal having high electron-emissive properties, such as thorium. Thorium is more refractory than barium and strontium-oxide coatings, and is therefore better able to provide long life in a high-pressure discharge lamp. With arc-heated thorium electrodes, the arc can be initiated when the electrodes are cold with alternating voltages as low as 130 volts. Thorium metal is inert with respect to quartz and does not require any processing to become electron-emissive. It is desirable that pure thorium be used. One simplified electrode design consists of a piece of thorium sheet or wire inside a tungsten helix as illustrated in figure 2. The seal wire also passes inside the helix and all three parts are clamped or spot-welded together. The thorium core is positioned slightly back from the free end of the tungsten helix in order to maintain the temperature of the thorium below the fusion point.

Averaged data in table III compares the thorium elec-

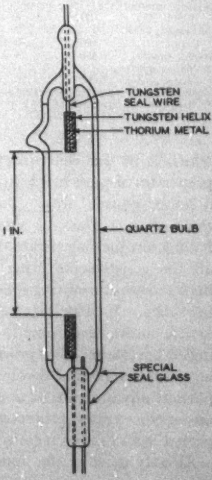

Figure 2. Diagram of quartz inner bulb for 100-watt type A-H4 mercury lamp

Table III. Comparison of Thorium and Oxide-Coated Electrodes in the 100-Watt A-H4 Mercury Lamp

Hours*	Lumens—Thorium Electrodes	Lumens—Oxide Electrodes
0	3,610	3,450
100	3,260	3,180
500	3,090	2,680
1,000	3,030	2,320
2,000	2,620	1,430

* These results are averaged on lamps turned on five hours and off one hour to approximate actual operating conditions in ordinary service.

trode with the former oxide-coated electrode in the 100-watt type *A-H4* quartz mercury lamp. These data were taken with lamps being tested on a burning schedule of five hours on and one hour off to approximate normal burning conditions. The advantage in using thorium becomes more obvious the longer the lamps are burned. The inherent life of thorium electrodes is very long. One instance of a lamp still operating satisfactorily after 16,000 hours seems to indicate that something other than electrode failure will determine the life of quartz lamps.

QUARTZ BULBS

The cost of fused quartz is another problem now in process of being solved. Large-scale use of it will be a partial solution in itself. There is promise of a low-cost substitute in the recently publicized "shrunk glass"[7] which is 96 per cent quartz and has approximately the properties of pure fused quartz. This glass is prepared in a rather unusual way. The desired shape is blown in a mold with a glass of somewhat normal characteristics having low melting point. By a special process practically all the constituents other than silica are removed. A high-temperature firing follows to consolidate the remaining silica. In this latter operation the shrinkage of the article corresponds roughly to that taking place in the firing of porcelain. The process is a radical departure from any other method of making fused quartz. It has the important advantage that abundant domestic raw materials are used. Other processes require quartz crystals imported from remote regions of Brazil.

Already most of the important operations in manufacturing quartz lamps are being done with the aid of machines. The use of machines is eliminating the high cost that has been synonymous with quartz working for many years. Contrasted with mercury lamps, sodium-vapor lamps are still exhausted by "trolley" exhaust which is slower and more expensive. The more complicated design of sodium lamps does not lend itself readily to automatic operations.

Table IV. Characteristics of High-Intensity Mercury Lamps

Lamp Type	Watts	Mercury Pressure (Atmospheres)	Lumens Per Watt	Maximum Brightness (Candles Per Sq Cm)	Guaranteed Life*
A-H1, glass	400	1.0	40	50	2,000
A-H2, glass	250	0.5	30	50	2,000
A-H3, quartz	85	25–30	35	900	500
A-H4, quartz	100	8–10	35	400	1,000
A-H4, quartz (black UV)	100	8–10			1,000
S4, quartz (sun lamp)	100	8–10	35	400	400
A-H5, quartz	250	4–5	40	300	1,000
A-H6, quartz (water-cooled)	1,000	75–80	65	30,000	75

* Hours, except figure for *S4* lamp which indicates number of applications.

TYPE H QUARTZ MERCURY LAMPS

In table IV the characteristics of type *H* high-intensity quartz mercury lamps are recorded. The 100-watt size is available with any of three outer bulbs, shown in figure 3, each intended for a different use. The type *A-H4* for general lighting has a tubular Nonex bulb which transmits visible light but absorbs the strong ultraviolet radiation of the mercury arc. The *S4* sun lamp with the same quartz arc tube employs a glass outer bulb that transmits not only the visible range of wave lengths of 8,000 to 4,000 angstroms, but also the ultraviolet rays down to 2,800 angstroms. This lamp has approximately the same ultraviolet output as the older *S1* sun lamp, but consumes less than one-third the energy. The 100-watt *B-H4* lamp for special decorative and other uses is an efficient source of what is popularly known as "black" light. Its red-purple bulb filters out the visible radiation, but transmits the strong 3,650-angstrom radiation. Certain materials, such as zinc sulphide and anthracene, when exposed to this wave length will fluoresce, emitting visible light of various colors. Such materials are used in paints that are to be floodlighted with "black" light to create attractive decorative effects.

For all three forms in which the 100-watt lamp is made, the high-pressure mercury arc is more efficient than a low-pressure arc. The radiation from a low-pressure mercury arc is largely the 2,537-angstrom resonant line. As the mercury pressure is increased this radiation is absorbed by the mercury vapor itself, and, instead, a larger proportion of the longer wave lengths is radiated. Hence the efficiency of visible and near-visible ultraviolet radiation is increased with increased mercury pressure.

The next larger lamp is the 250-watt type *A-H5* lamp which besides general lighting is particularly suited to the

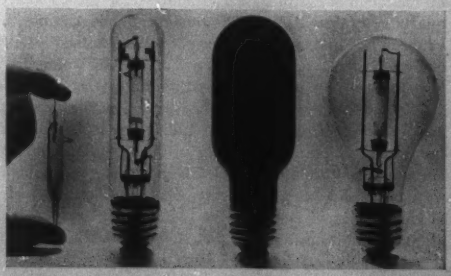

Figure 3. Three 100-watt quartz mercury lamps (left to right): quartz inner bulb, type A-H4, type B-H4, type S4

requirements of highway lighting (figure 4). Its small arc stream, which may be operated in a horizontal position, can be efficiently utilized with small inexpensive luminaires.

A 400-watt quartz lamp now being developed for general use may be compared with type *A-H*1 glass 400-watt lamp with which it will be interchangeable (figure 5). The efficiency is about 20 per cent higher, and because the arc in quartz is shorter and more concentrated, the utilization of the light produced may be higher. Angular or horizontal burning is made possible. The glass lamp is limited to vertical burning as the convection currents in the mercury vapor push the hot arc against the glass envelope and soften it when the lamp is burned in any other position. The convection currents are enough weaker in the smaller quartz bulb that the lamp may be operated in any position.

Both 250- and 400-watt quartz lamps have been extensively used in the New York World's Fair, the 250-watt lamp for floodlighting trees and the 400-watt lamp for the Lagoon of Nations fountain and the Perisphere.

The water-cooled 1,000-watt type *A-H*6 is the highest-pressure mercury lamp. Operating at 75 atmospheres mercury pressure, the arc has the highest brightness and efficiency of any mercury lamp now available. By concentrating 1,000 watts into a chamber an inch long and one-tenth inch in diameter, a 65,000-lumen light source is produced having a brightness of 30,000 candles per square centimeter or about one-fifth that of the sun. The quartz bulb, together with the water-cooling jacket, is smaller than the 250-watt air-cooled lamp, as can be seen in figure 4. Its uses have been mostly in special projection applications where high brightness is desired.

NEW APPLICATIONS

As to the future, it is expected that the high efficiency of these lamps will bring them to new fields. One example might be headlights on moving vehicles—automobiles, airplanes, and railway locomotives—where more light with minimum generator capacity is always to be desired. Another is in television or moving-picture-studio lighting where high levels of illumination are accompanied by intense heat radiation with low-efficiency light sources. The water-cooled mercury lamp is particularly suited to this service because the water acts as a filter, absorbing the long-wave infrared or heat radiation. The light is therefore much cooler than that obtained from incandescent lamps or carbon arcs.

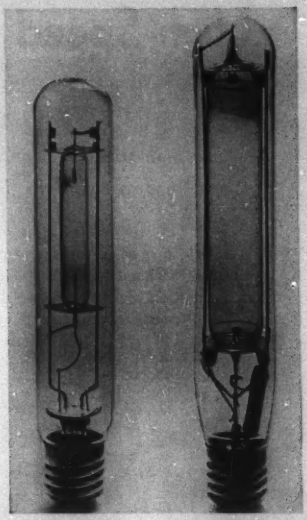

Figure 5. Two 400-watt mercury lamps (left to right): quartz lamp (under development), glass lamp type A-H1

For motion-picture projection, short high-current mercury arcs are being considered. For highway lighting, quartz high-intensity mercury lamps are widely used in Europe, and trial installations are being planned in the United States.

It is expected that greater general use of quartz mercury lamps will be brought about by inducements of lower cost resulting from better production methods and by longer life which is inherent but difficult to predict in discharge lamps as it has been found to be with vacuum tubes.

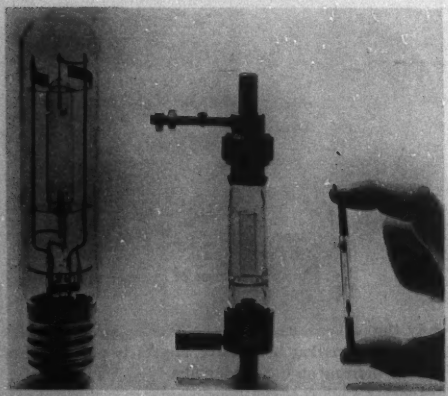

Figure 4. A 250-watt and a 1,000-watt quartz mercury lamp (left to right): 250-watt type A-H5, water-cooling jacket for A-H6, 1,000-watt type A-H6

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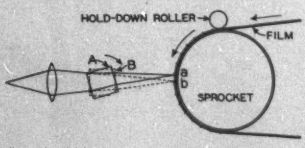
High-Speed Motion Pictures Aid Design

J. R. TOWNSEND

The high-speed motion picture camera is a useful tool in studying rapid motion and has assisted in improving the design of electromechanical apparatus

THE early history of engineering was concerned largely with static mechanics, but the modern age has become concerned with high power, speed, and complicated mechanical movements much too rapid to be seen directly.



Film moves continuously; light from object passes through cubical prism *AB* before reaching film, which keeps the image stationary on the film by refraction; when the prism moves from *A* to *B*, the image moves from *a* to *b*

Figure 1. Diagram illustrating principle of operation of camera

This trend has become of increasing importance in the Bell System, with the development and improvement in speed and accuracy of machine-switching apparatus. In order correctly to design the necessary electromechanical apparatus to fulfill these requirements, it is necessary to be able to analyze mechanical motion with great precision.

There are a number of available tools for the analysis of mechanical motion. If the motion is within the range of our sense of perception it may be followed by eye and the position of a point in terms of time may be plotted by direct measurement. If the motion is too rapid to be followed by eye and is repetitive it may be analyzed by means of a stroboscope. There are various forms of this device; they consist princ pally in using an intermittent shutter or flashlight which bears a definite phase relationship with the motion under investigation. It is also possible to use this flashing light, if it is intense enough and its duration short enough, to photograph successive positions of a moving object. This will give a series of still pictures from which the motion may be plotted and analyzed. This is precisely the method used by Professor Harold E. Edgerton (A'27, M'32) at Massachusetts Institute of Technology in taking instantaneous pictures of many familiar actions that are beyond our sense of perception, such as the beat of a fly's wings, the details of the breaking of an egg, and many other subjects which are presented in his book "Flash". The same device is used by him to make high-speed motion pictures. Here the film is driven continuously through a camera and the flashing light is of such short duration that a series of images is photographed without blurring on the moving film.

Figure 2. High-speed motion picture camera and lighting equipment

Figure 3. Interior of camera

Another method of obtaining a series of pictures of motion applicable to relatively slow movements is by means

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Figure 6

Figure 4. Drop of milk falling into cup of coffee

Figure 5. Breaking of Charpy specimen of hard rubber; note time scale at right

Figure 6. Breaking of impact specimen of glyptol as viewed by polarized light at the time of being struck by the impact hammer; these are said to be the first strain pictures taken with polarized light at high speed

Figure 7. Operation of teletypewriter cam and idler (*A*) and same mechanism (*B*) after redesign; note how much more closely the idler followed the cam after redesign

Figure 4 Figure 5 Figure 7*A* Figure 7*B*

Figures 4 to 7. Enlargements of selected frames from high-speed motion pictures, illustrating versatility of this method of studying high-speed motion

Figure 8. Selected enlarged frames from a high-speed motion picture of the blowing of an ordinary plug fuse

of the ordinary motion-picture camera which uses a mechanical method of bringing the film into position and holding it for sufficient time to permit the proper photographic exposure. This is usually accomplished by means of a rotating shutter, and the film is pulled down a frame at a time by a mechanically operated claw mechanism which engages perforations in the film. Such a camera is severely limited in the number of frames or pictures it may take in a second. The usual limitation is about 80 frames per second, although speeds up to 300 per second are practical. Most of the slow-speed motion studies of athletic events and the like are taken with such a camera. This camera is also useful in taking pictures of mechanical motion of moderate speed.

To obtain a series of pictures of extremely rapid motion would be impossible with such a camera, as the mechanical inertia of the claw mechanism and film would prevent the camera from operating at the requisite high speed with sufficient fidelity of positioning the film uniformly and smoothly behind the lens. Other means of holding an image stationary with respect to the film for sufficient time to permit a photographic exposure must be devised.

A method of doing this, which is employed in the camera developed at the Bell Telephone Laboratories (figures 2 and 3), is illustrated in figure 1. The rays from a point of the object are converged by the lens on the front face of the cube at "*A*"; they are refracted by the glass to the opposite face, pass through it, and form an image on the film at "*a*". When the film has reached a point "*b*", this compensating cube has moved to position "*B*", thus for a brief period the film and the image move at the same speed. The duration of each such exposure is controlled by the speed of rotation of this compensating cube and by the angular height of an aperture in front of each of the four faces of the cube. The cube rotates 1,000 times per second on taking 4,000 pictures per second. The cube is driven by spur gears from a main shaft which is connected directly to a 1/5-horsepower motor. The take-up reel is driven by a separate motor which tends to run faster than the motor driving the sprocket, gear train, and optical compensator, since the latter is more heavily loaded. This causes the film to wind up smoothly. Film passes through the camera at the rate of 70 miles per hour—100 feet in an interval of $1\frac{1}{2}$ seconds—for a taking speed of 4,000 frames per second; 16-millimeter film is used.

These pictures may be analyzed in two different ways. They may be projected or otherwise examined individually or they may be projected as moving pictures at 16 frames per second where the motion may be observed at 1/250 of normal speed. Both of these methods are employed at the Bell Laboratories.

One of the advantages of this method of taking high-speed motion pictures is that subjects may be given studio type illumination in order to bring out the fullest modeling of the subject. The same principles of lighting are used as are employed in any well-equipped studio. The principal difference resides in the intensity of illumination, for using such a high taking speed obviously requires intense lights. Portable light units have been developed which employ tungsten lamps rated, for example, to operate at 70 volts and 750 watts but operated at 120 volts. This raises the temperature of the filament and hence the intensity of the light source. The light intensity varies from 10,000 to 500,000 foot-candles, depending upon the subject, the speed of taking, and the area to be covered. The images of the filaments are projected on the object by using elliptical mirrors behind the lamps. Because of the intense heat, liquid filters are used to absorb this radiation.

A particular field of application for the high-speed motion-picture camera, as already stated, is to study irregular motion that cannot be analyzed by a stroboscope. A further advantage is that the lighting methods that have just been described may be employed, which give better photographic image formation than can be had by a flashing light. It is also possible to work at higher speeds than are practical with a flashing light mechanism because of the difficulty in the latter case of getting sufficiently intense light.

Figures 4 to 8, inclusive, illustrate the usefulness of high-speed motion pictures in studying various types of motion. Illustrative examples of their application to the solution of telephone-apparatus development problems are:

1. Study of mechanism of the teletypewriter (figure 7) which led to redesign of cams and changing the inertia of cam idlers; this was instrumental in reducing impact and noise of operation of the equipment.

2. Study of the vibration of the structure of relays has led to changes in the period of vibration of the component parts and reduction in contact chatter.

3. Study of elastic impact of handset handles has resulted in improved design and material more resistant to service.

4. Study of the motion of the automatic telephone-switching equipment has resulted in design improvements. In fact, all mechanical apparatus that operates at a speed beyond the normal sense of perception is photographed so as to assure that the mechanical parts are operating in the best possible way.

5. High-speed motion pictures have been made of the human vocal cords.

Ceramic Insulating Materials

HANS THURNAUER

A review of the various ceramic materials used as insulation in electric circuits, their composition, methods of manufacture, and characteristics

IN 1898, Professor Reginald Aubrey Fessenden, one of the ablest authorities on the subject of insulation of his time, made the following statement:[1] "I have no hesitation in saying that there are not more than one or two companies in the United States whose insulations are worth more than so much bare cotton cloth after two years' service." The remark referred more especially to the varnishes with which tapes, cloths, and papers were impregnated, but may have been applied to other types of insulation as well. At this time almost any available material which seemed suitable as an insulator was used without much testing or questioning.

Charles P. Steinmetz was among the first to recognize the need for investigating electrical insulating materials, and some of his studies dealt with the dielectric properties of ceramic materials—lava, porcelain, and glass—which were among the first used as electrical insulators. Today the production of technical ceramic products represents a romantic survival of one of the oldest arts developed by the human race. It can be stated, without exaggeration, that our modern electrical system could not be built without the use of ceramic insulation. It is to the credit of the ceramic engineer that an age-old technique has been developed to such perfection that it meets the requirements for modern electrical insulation.

Ceramic materials are used successfully in four general types of electrical applications: low voltage, high voltage, electrical heating, and high frequency. Before discussing the subject further, however, perhaps a definition would be helpful. "Ceramics" is derived from the Greek word, "keramos", meaning potter's earth or clay, a substance found in abundance all over the world. In modern usage, however, it includes all materials that are inorganic and brought to permanent shape and hardness by high temperatures; the heating process results in partial or complete fusion of the constituents and in the formation of compounds not present in the raw materials. This definition comprises a large number of mineral products such as abrasives, cements, enamels, glass, structural clay products, refractories, terra cotta, and white ware.

ELECTRICAL PORCELAIN

Porcelain is, undoubtedly, the best known material among ceramic insulation products. Electrical porcelain is a vitrified mixture of complex silicate compounds bonded together in a glassy matrix. The chief raw materials for porcelain manufacture are of plastic and nonplastic nature: clays, on the one hand; feldspar and flint, on the other.

The plastic constituents, the clays, consist of two kinds: china clay and ball clay. Both of these are hydrous aluminum silicates, resulting from the decomposition of feldspathic rock. Of the two types, china clay is the purer material and burns to a white color. Ball clays have been carried further during the decomposition process and are finer in particle size than china clays; they are mixed with organic matter, such as lignites, which gives them a dark color, but also high plasticity. During the firing process the organic matter is burned out completely and the resultant burned clay is usually of a cream color.

The term "ball clay" is derived from the old English way of mining the material. It was mined in open pits and taken out in the form of balls weighing approximately 33 pounds each. China clay is preferable in body compositions because of its white burning color and its good electrical properties in the fired body. A certain amount of ball clay is necessary, however, to obtain good dry bonding strength and high plasticity, especially for the production of complicated shapes.

It is usual practice to blend clays from various deposits to obtain greater uniformity and to get a combination of properties that cannot be found in one single raw material. The clays are selected for their plasticity, drying shrinkage, dry strength, color, electrical properties, and so forth.

The nonplastic constituents are feldspar and flint. Feldspar is an alkaline aluminum silicate and may be either rich in soda or potash; for porcelain production only the potash variety is used. Feldspar is found in rock formation and mined by quarry operations, then crushed and ground. Since the fusion point of feldspar depends to a large extent upon the fineness of grinding and composition, it is essential that uniformity in particle size and in chemical analysis be maintained, to keep the vitrification range of the porcelain body constant. During the heating process, feldspar fuses and dissolves part of the clay and flint in the body. Flint is ground rock quartz of high purity. It remains inert during firing, but changes its crystalline form. The addition of flint to porcelain bodies reduces firing shrinkage and warpage.

The Chinese, masters in the manufacture of vitrified porcelain, very fittingly compared clay with the flesh, flint with the bones, and feldspar with the blood of the human body.

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1. For numbered references see list at end of article.

	Porcelain		Steatite				
	Wet Process	Dry Process	General Grade	High-Frequency Grade	Low-Expansion Bodies (Cordierite)	Refractory Porcelain	
Electrical Properties							
Power factor, per cent, at 1 kilocycle	1....	1....	0.20....	0.06....	0.40....		
Power factor, per cent, at 1 megacycle	0.7....	0.8....					
Power factor, per cent, at 10 megacycles			0.18....	0.04....	0.30....		
Dielectric constant	6.5–7.5....	6.0–7.5....	6.0–6.2....	5.8–6.0....	5.0....		
Dielectric strength, volts per mil	0.2*:280....		¹/₄":200....	¹/₄":240....	¹/₄":100....		
Capacitance change per deg C			+1.6×10⁻⁴....	+1.4×10⁻⁴....			
Volume resistivity, ohm-cm, at room temperature	1×10¹⁴....	7×10¹³....	1×10¹⁴....	1×10¹⁴....	1×10¹³....	1×10¹³....	
Te-value†, deg C	300–500....	300–500....	550....	900....	650....	550....	
Mechanical Properties							
Specific gravity (bulk)	2.4....	2.3....	2.5....	2.6....	2.1....	1.9....	
Water absorption, per cent	Nil....	0.5–2....	Nil −0.1....	Nil −0.1....	0.1–1.0....	10....	
Hardness (Mohs scale)	7....	7....	7.5....	7.5....	7....	7....	
Tensile strength, lb per sq in. (multiply by 10³)	6.0....	1.0–3.5....	7.5....	8.0....	2.0....	0.8–1.0....	
Compressive strength, lb per sq in. (multiply by 10³)	55.0....	30–40....	85....	85....	50....	20–30....	
Modulus of rupture, lb per sq in. (multiply by 10³)	11.0....	6.0–6.5....	18–22....	20–24....	8–10....	3.0–3.5....	
Resistance to impact, ft-lb Charpy per sq in.	0.9–1.1....	0.7–0.9....	1.6....	1.9....	0.7–1.0....	0.5–0.7....	
Modulus of elasticity, lb per sq in. (multiply by 10⁶)	7–14....	7–12....	13–15....	13–15....	7....		
Thermal Properties							
Softening temperature, deg C	1,600....	1,600....	1,430....	1,430....	1,400....	1,450....	
Maximum operating temperature, deg C	1,000....	1,000....	1,000....	1,000....	1,200....	1,200....	
Linear coefficient of thermal expansion, per deg C (multiply by 10⁻⁶)	4....	3–4....	7....	7....	1.8–2.0....	2.5....	
Thermal conductivity, cgs	0.0025....	0.0025....	0.006....	0.006....	0.003....	0.002–0.003....	
Mean specific heat, g-calories per g per deg C	0.2....	0.2....				0.22....	

† Temperature in degrees centigrade at which one-centimeter cube has the resistance of one megohm.

In making porcelain bodies, it is essential that an intimate mixture of the ingredients be obtained. This is done by mixing or blunging the finely ground raw materials with water. Where best electrical and mechanical properties are desired, bodies are frequently prepared by pregrinding the nonplastics, flint and feldspar, in pebble mills and adding these wet-ground ingredients to the water-suspended clays in the blunger. The finer structure of the feldspar and flint gives a better mechanical mixture. This makes the materials more active in their properties and effects a better performance of the body throughout the manufacturing process.

After blunging, the body is passed over screens and a powerful electromagnet to remove all traces of free iron which may give faulty spots in the final ware. The body is stored in agitated bins and is ready for filter pressing. The filter presses squeeze out surplus water and produce plastic cakes of uniform moisture content which are ready to go into the pugmill. A pugmill may be described as a screw conveyor which exerts a kneading action to the plastic body and brings particles closer together. Modern pugmills are fitted with vacuum chambers to remove enclosed air.

Electrical porcelain is formed by the three main processes: wet forming, casting, and dry pressing.[2] For wet forming, the plastic material from the pugmill is cut into blanks of desired size and formed either by the hand process, called jiggering, or by machine pressing. The blanks are placed into plaster-of-paris molds. In the jiggering process the mold with the lump of body is set into a revolving head and the ware is formed by a forming tool which is pulled down into the mold on a vertical axis or swung over the arc of a circle.

For high-voltage porcelain, especially suspension insulators, machine pressing is used. In this process, the mold is stationary and the forming tool, traveling on a vertical axis, revolves. After shaping, the molds with the formed insulator parts are put into a release dryer. The plaster-of-paris mold is porous and absorbs moisture from the plastic body. During the drying process, the plastic body shrinks and pieces can be taken from the mold as soon as sufficiently stiff to be handled without distortion. They are then put through a second dryer where they become leather-hard, so that they can be trimmed to accurate dimensions. After trimming, pieces are sent through a final dryer after which they are ready for glazing.

A second method of making wet-process porcelain is to extrude the plastic material into tubes or bars. Either auger machines or hydraulic presses are used for extrusion. The extruded pieces are cut to length and finished after the material is partly or entirely dry. The blanks are turned on a lathe to the desired shape.

Difficult and unsymmetrical shapes can be made by the casting process. The body in cream-like consistency, the so-called "slip", is poured into a plaster-of-paris mold. By the addition of certain deflocculants, like silicate of soda and soda ash, it is possible to produce a fluid material that will pour in a fine stream and contain only a little more water than the plastic material used in wet processing. The plaster-of-paris mold is filled with the casting "slip" and allowed to stand for a certain length of time. The porous plaster absorbs part of the water from the liquid slip and a crust of body forms against the wall of the mold, increasing in thickness the longer the liquid slip remains in the mold. After the deposit has reached the desired thickness, the slip, still liquid in the center, is

Rutile Bodies		Refractory Bodies				Glass				Mycalex	
High Dielectric Constant	Variable Temperature Coefficient of Capacitance	Lava (Radio Grade)	Beryllium Oxide (BeO)	Magnesium Oxide (MgO)	Aluminum Oxide (Al_2O_3)	Flint	Crown	Radio Pyrex	Fused Quartz	General Grade	Radio
....0.08....	0.06....	0.30				0.45....	1.0....	0.28*....	0.03		
						0.40....	0.95....	0.20....	0.02....	0.23....	0.20
....0.06....	0.04....	0.25									
....85....	12–85....	5.3–5.4				7–9....	6–7....	4.48....	3.7–4.2....	8.3....	7.5
....1/4":200....	1/4":200....	1/4":100						1/16":400	1/4":350....	0.2":340	0.2":340....	0.2":360
										1/8":200		
−6.5×10⁻⁴....	+1.2 to −6.5×10⁻⁴											
....1×10¹⁴....	1×10¹³....	1×10¹³–10¹⁴				1×10¹³....	1×10¹³....	1×10¹⁴....	5×10¹⁸....	5×10¹³	
		700....	950–1,100....	850–1,050....	850–1,050		350....	360....	721		
....3.9....	3.6–3.9....	2.8....	2.0–2.5....	2.6–2.8....	2.6–2.8....	3.7....	2.5....	2.25....	2.2....	3.44....	2.95
....Nil....	Nil....	1.5....	20–50....	20–50....	20–50....	Nil....	Nil....	Nil....	Nil....	0.03....	0.003
....8....	7.5–8....	6				5....	5....	5....	7....	3–4	
....6....	6....	1.8				3–6....	2–5....		8....	5–7	
....80....	80....	20				6–10....	10–30....	40....	20....	22–30	
....20....	20....	14								15–20....	14–19
....1.8....	1.8									1.16	
....15....	15					9.3....	9.3....	8.86....	10.15		
....1,500....	1,350–1,500....	1,500....	2,500+....	2,500+....	2,000+		1,100....	600....	1,450....	450–500....	450–500
....300....	300....	1,000....	2,000+....	2,000+....	1,450+			520....	1,000....	300....	300
....7–8....	6–8....	9....	7.5....	13.4....	7.9....	7.9....	8.9....	3.2....	0.54....	8	
		0.005				0.0020....	0.0025....	0.0027....	0.0036		
					0.18–0.20....	0.12....	0.16....	0.20....	0.25....	0.2	

* Per cent power factor at 3 kilocycles.

poured out and the cast piece left in the mold until it is sufficiently dry for handling without deformation. After removal from the mold, the method of finishing is similar to that of the wet process.

For dry pressing, the filter cakes are partially dried and disintegrated to a grainy mass. The moist powdered material is put into steel dies and molded under pressure. Porcelain presses may be either hand or power operated. The ware produced by dry pressing is not as dense in structure as that produced by wet process or casting. The dry-pressed porcelain is suitable for only low-voltage applications.* It can be worked to good dimensional accuracy, however, especially when made on automatic presses. Special care must be taken with regard to particle size, moisture content, and pressure to insure a uniform product.

As distinguished from the slip method, requiring blunging, filter pressing, and re-mixing, "controlled mixing" has been introduced in several large plants during recent years. This is done by mulling a plastic body having a moisture content of from 9 to 27 per cent. All elements of the mix are proportioned by weight directly into the muller-type mixer, with the proper amount of liquid added, and mulled until complete distribution of raw materials and dispersion of liquids is accomplished. Frequently, chemicals which lower the surface tension of the water and help to speed up penetration of moisture through the clay mixture are added. The amount of liquid, mulling time, and moisture content are positively controlled, resulting in close adherence to required properties of the body, strict uniformity of each batch and high plastic strength. Mulling time varies from 12 to 25 minutes per batch, depending upon raw materials and other factors. The advantages, especially as to speed in operation, over the old method are obvious.

After the ware has been dried, a glaze frequently is applied. A glaze is nothing else but a layer of glass melted to the surface of the body. The glaze on a porcelain body consists essentially of the same raw materials as those used for the body, but in different proportions. The glaze mixture melts to a glass at the temperature at which the insulator is fired. Colored glazes are produced by adding coloring oxides to the glaze mixture. It is essential that a glaze "fit" a body, that is, its thermal expansion and contraction must correspond to those of the underlying body, especially if the piece is used under severe mechanical and thermal conditions. A well-fitting glaze may not have *exactly* the same expansion curve as the body, but can have a slightly lower expansion, thus keeping the underlying body under compression. It has been shown that variations in glaze fit can affect the mechanical strength of porcelain by 200 to 300 per cent.[3]

After glazing, the ware is ready to go into the kiln for firing. The porcelain parts are placed in "saggers" or refractory containers which are stacked on top of each other. These saggers are either put into periodic kilns or on cars to go through continuous tunnel kilns. Firing temperature of electrical porcelain is usually above 1,250 degrees centigrade.

A number of physical and chemical changes occur in the porcelain body during firing. A small amount of mechanically held water is driven out before the temperature reaches the boiling point of water. The next change occurs when the chemically combined water in the clay is driven out. This occurs at about 450 degrees centigrade. With further increase of temperature, the glaze be-

gins to flow and cover the surface of the porcelain. Finally, the softening and fusing of the feldspar grains occur and the liquid spar covers the clay and flint grains. At about the same temperature, the clay particles break up without becoming liquid and change into other crystalline forms of which parts are dissolved in the spar. Even some of the flint is dissolved. These various processes of melting, solution, recrystallization, and crystal changes may be varied with temperature and length of heating, and porcelain with different properties can be produced by merely changing firing rate and temperature.

After firing, the ware must be cooled slowly, to prevent the development of internal strains and cracking. Finally, it is tested, inspected, and ready for shipment, or assembly with metal parts.

Porcelain may be classified, according to its application, into low-voltage and high-voltage porcelain. For low-voltage use it is generally made by the dry-pressing and extrusion processes, whereas high-voltage porcelain is made by the wet and casting processes.

Porcelain for low-voltage use again is graded into four general classes by degree of vitrification:[11]

Class 1 includes parts that have less than 0.25 per cent moisture absorption on whole specimens and less than 0.50 per cent moisture absorption on broken specimens after immersion in boiling water for 30 minutes. Parts for severe atmospheric conditions, such as bases and sockets for outdoor use, fall in this group.

Class 2 permits a moisture absorption between 0.50 and 1 per cent on whole and broken pieces and comprises pieces used under semi-severe service, such as in basements or in protected apparatus installed in outside locations, like tubes and terminal blocks.

Class 3 limits moisture absorption between 1.25 and 2 per cent and applies for porcelain parts, such as screw eyes and protector blocks.

Class 4 includes all porous parts with more than 2 per cent moisture absorption which must have good thermal-shock characteristics, such as resistor cores.

For reduction of moisture absorption, especially in radio receivers, impregnation with organic, moisture-repellant substances, such as ceresin wax, is common practice. The pieces are heated to the melting point of the wax and dipped into the molten wax, preferably under vacuum. Surplus wax is thrown off by centrifuging. Pieces thus impregnated show surprisingly good moisture characteristics. Of course, they cannot be used at temperatures above the melting temperature of the wax without destroying the impregnating film, nor is the dielectric strength of the material improved by such a procedure.

Generally speaking, it may be said that low-voltage porcelain is a desirable insulating material where good mechanical strength, heat resistance, lack of fatigue and cold flow, rigidity, and permanence and, last but not least, low production cost are desirable properties. The disadvantages of porcelain over other types of insulation materials are: low impact strength, limits as to dimensional tolerances, and the necessity of assembling metal parts into finished pieces, rather than molding them permanently into place.

Specifications for high-voltage porcelain are very exacting. It must be vitrified to such a degree that no penetration occurs on a broken surface after immersion in an alcohol-fuchsin dye solution for 15 hours under a pressure of 4,000 pounds per square inch. This high density is of importance for high-voltage work because absorption of moisture, even in traces, results in electrical breakdown under high-voltage conditions.

The three most important properties of high-voltage porcelain are: dielectric strength, mechanical strength, and resistance to sudden temperature changes. All three properties in the very highest degree are not likely to be found in any one body, because they are dependent upon the composition of the body and the various ingredients produce different properties. It has been found that high dielectric strength is characteristic of high feldspar content, high mechanical strength is a function of high quartz content, and high resistance to temperature changes results from high clay content. G. J. Gilchrest and T. A. Klinefelter[4] have drawn a triaxial diagram showing possible porcelain compositions with properties to be expected. Good high-voltage porcelain must have a good working percentage of the three properties, and a good balance is preferable to an optimum in only one direction.

HIGH-FREQUENCY INSULATING MATERIALS

Insulating materials for high-frequency applications require certain properties which are of less importance at low frequencies. As frequencies increase, dielectric losses must be considered.

An insulating material in an electric field consumes part of the electric energy and transforms it into heat. Therefore, "loss" of energy occurs. The loss, N, may be expressed by the following equation:

$$N = E^2 \cdot 2\pi f C \tan \delta$$

where E is the potential, f the frequency, C the capacitance, and tan δ the loss factor. The capacitance C can be expressed by two factors—the dielectric constant ϵ and a constant K which depends upon the shape and field position of the insulator. The formula, therefore, may be written:

$$N = (E^2 \cdot 2\pi f K)\epsilon \tan \delta$$

and it can be seen that the dielectric constant ϵ and the power factor tan δ are two material constants that are important for the dielectric losses in the insulating material. It further shows that assuming constant loss factor the lost energy increases with increasing frequency f, and the product ϵ tan δ ought to be kept as low as possible, if the insulating material is used merely as a support for a conductor. Where the insulator is used as a dielectric medium in a capacitor ϵ ought to be high, so as to get sufficient capacitance without making the capacitor too bulky or the dielectric too thin. In any case, tan δ ought to be low.

Insulating materials for high-frequency use must be rigid and chemically inert. In order to avoid "drift," temperature changes should have no effect upon them. A low coefficient of thermal expansion, therefore, is another requirement for an insulating material used in high-frequency circuits.

In vacuum tubes, insulating materials are required

which can easily be degasified and which have low dielectric losses and high insulating resistance at elevated temperatures.

Summarizing, insulating materials with the following properties are required for high-frequency use:

1. Vitrified, mechanically strong materials with low dielectric constant and low power factor for general insulation purposes.

2. Vitrified insulating materials with high dielectric constant and low power factor for capacitors.

3. Insulating materials with low coefficient of thermal expansion for temperature-independent oscillating circuits.

4. Porous or vitrified insulating materials with low dielectric constant and low loss factor for vacuum-tube spacers.

Fused quartz may be regarded as the ideal material for high-frequency purposes because it combines very low dielectric loss with stability and rigidity. Its general application in transmitters or receivers is prohibitive, however, because of high cost of manufacture and because of the limited possibilities of molding this material. Insulators made of quartz glass may be used to some extent in transmitters for ultrashort waves or in precision instruments; they cannot be used where economy of production is a deciding factor.

The manufacture of fused-quartz articles is a highly specialized art. Clear fused quartz is made from high quality clear quartz crystals, or white sand in sufficient state of purity. The raw materials must be acid-treated to remove impurities.

Rods and tubes are generally made in two stages.[5] The crystals are closely packed in graphite crucibles, vacuum applied to the furnace, and the temperature raised to 1,800 degrees centigrade. Enclosed air bubbles rise to the surface of the fused silica. After release of vacuum, pressure is applied by the introduction of nitrogen to reduce the volume of the remaining bubbles to the smallest possible dimensions. The resultant slug is pure and clear. For the forming of small rods and tubes, a slug is heated in a second graphite crucible. A loaded graphite piston is located in the crucible on top of the slug and, as the latter is fused, the molten silica is gradually extruded as a rod or tube through appropriately arranged holes in the descending piston.

Tubes and rods are also made by fusing sand around a central resistor. The core, or resistor, is removed and the silica cylinder withdrawn for drawing into a tube. Other shapes are made according to common glass-manufacturing practice.

Fused silica is an exceptionally good insulator; its mechanical strength is high and its dielectric losses very low. One of the outstanding properties of fused silica is its low coefficient of thermal expansion.

The difficulties of manufacturing quartz glass insulators prohibit their general use, and it is necessary, therefore, to look for other insulating materials with low dielectric losses. Steatite materials combine low dielectric losses with high mechanical and dielectric strength and economy in production.[8]

Steatite is understood to be a group of ceramic materials which contain the hydrous magnesium silicate, talc, as a predominant constituent in the unfired body. Steatite bodies of this definition are fired to vitrification at a temperature of approximately 1,400 degrees centigrade. The final products of thermal decomposition of talc, heated to 1,300 degrees are clinoenstatite and cristobalite; in fired steatite bodies, these crystals can be readily identified.

The microstructure of a steatite body is different from that of a porcelain body. Under the microscope, it can be seen that steatite bodies have a very uniform structure, with a predominance of clinoenstatite crystals. Porcelain, however, contains glassy and crystalline matter in about equal portions. This uniformly crystalline microstructure combined with low alkali content is regarded as being responsible for the low dielectric losses of steatite bodies. Reduction of alkalies and further improvements of microstructure resulted in the development of steatite bodies with very low dielectric losses, approaching those of pure quartz.

Steatite insulators are made according to ceramic manufacturing methods described under porcelain, with the exception of the dry-pressing process which is somewhat different from known porcelain practice. Finely powdered talc can be compressed into a compact mass without the addition of moisture. The process, therefore, is truly a dry process. Dry-pressed steatite parts leave the die in a sufficiently hard condition so that they can be handled without danger of distortion and can go directly into the kiln without preliminary drying. They can be manufactured on automatic presses and can be made to great accuracy and density. As examples of dry-pressed steatite parts used in radio receivers may be mentioned trimmer-capacitor bases, socket bases, tube bases, and bushings.

The second group of ceramic materials for high frequency use comprises materials distinguished by a comparatively high dielectric constant and, therefore, suitable for use as dielectrics in capacitors.[14] The manufacture

Removing plastic cakes from filter presses, in porcelain insulator production

Westinghouse

of ceramic bodies with high dielectric constant is one of the latest developments in the ceramic industry. The chief raw material for these materials is titanium dioxide, TiO_2, which has long been known to have a high dielectric constant. The natural mineral, rutile, has a dielectric constant of 183 parallel to its crystal axis and 89 perpendicular to the axis. A crystal mixture has a dielectric constant of 110. By adding fluxes to titanium dioxide, it is possible to produce vitrified ceramic bodies that consist chiefly of a mixture of rutile crystals. The addition of fluxes causes a decrease of dielectric constant to less than 110. The power factor of such bodies at high frequencies is low and within the limits of low-loss ceramic materials. At low frequencies, however, it increases considerably.

Bodies with high dielectric constant of rutile composition are characterized by high negative temperature coefficient of capacitance, which means that the dielectric constant decreases with increasing temperature. This is in contrast with most solid insulating materials which have a positive coefficient. For instance, the dielectric constant of wet-process porcelain changes from 8 at room temperature to 63 at 100 degrees centigrade.

By incorporating, in correct proportions, materials having negative and positive temperature coefficients of capacitance, it is possible to make ceramic bodies that have certain temperature coefficients. Such capacitors are manufactured and served as compensating units in temperature-independent oscillating circuits. They are usually made as thin-walled tubes consisting of the ceramic material with metallic layers fired directly on the outside and inside of the tube. The total unit may be moisture-proofed with lacquer, wax, or other organic impregnating compounds or enclosed in a moistureproof ceramic casing. The units are extremely stable and show excellent characteristics under humid conditions.

Thermal expansion coefficients of ceramic materials lie within the range of 1 to 10 times 10^{-6} per degree centigrade. Oxides like those of magnesium (MgO), titanium (TiO_2), and zirconium (ZrO_2), and compounds of these oxides among each other have high coefficients. Steatite bodies have coefficients between 6 and 7 times 10^{-6}; hard porcelain bodies have somewhat lower values—3 to 4.5 times 10^{-6}. Materials of low coefficient of expansion are those which show values below 2 times 10^{-6}. Quartz glass is one of these materials and in this group also belong the so-called "cordierite" bodies which contain a large amount of cordierite crystals ($2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2$). Such materials are used to some extent in the construction of temperature-independent oscillating circuits; they are also of importance for parts exposed to sudden temperature changes, such as resistor cores, heating-element supports, and arc chambers.

Refractory ceramic materials of low dielectric losses find various applications as insulators in vacuum tubes. These materials are usually of the porous type. A finely porous material consists of a large number of fine grains or crystals which are connected with each other on only parts of their surfaces. The voids between the grains are open and, during evacuation, it is possible to remove all traces of gases throughout the porous material. Another advantage of porous materials as insulators in vacuum tubes is that no coherent metal layers can deposit over the surface of the insulator, in case metal vapors are given off in the tubes.

The material most widely used for vacuum tube spacers is "lava," or burned soapstone. The raw material is the well-known hydrous magnesium silicate mineral talc which is machined in its natural condition and then burned to hardness under certain conditions of time and temperature (1,800 degrees Fahrenheit or approximately 1,000 degrees centigrade). For spacers in vacuum tubes, only selected materials are suitable, which must be as free from iron oxide as possible. For better evacuation, pieces are fired in a hydrogen atmosphere before use. These spacers made from natural stone have been replaced, to some extent, by materials made from powdered raw materials and dry-pressed under high pressure. Such spacers are usually made either from a material having powdered talc or alumina as the chief ingredient.

Vacuum-tube cathode insulators are made of refractory oxides of high purity.[17] These insulators get white hot during use and only the most refractory materials—such as beryllium oxide, magnesium oxide, aluminum oxide, or thorium oxide—are suitable for this purpose. The art of making these insulators has been perfected by only a few companies which make very small tubes, rods, and other shapes from these oxides. These insulators probably represent the smallest ceramic articles on the market.

GLASS

Glass is one of the oldest materials manufactured by man. It has been described as an undercooled liquid "whose rigidity is great enough to enable it to be put to certain useful purposes" (Morey).[19] Its chemical composition varies widely, but in general it can be said that silica (SiO_2) is the foundation of all commercial glasses, fused with such basic metallic oxides as soda and potash and with other oxides such as those of calcium, lead, barium, magnesium, and boron. The properties of glasses are primarily determined by their compositions.

Silica is ordinarily introduced into the glass batch as flint, sand in finely powdered form. For the manufacture of clear glass, it must be as free from iron oxide as possible. Alkalies are introduced in the form of soda ash (Na_2CO_3) and potash (K_2CO_3); lime is added as limestone ($CaCO_3$); barium, as witherite ($BaCO_3$); and lead, as red lead (Pb_3O_4). Furthermore, cullet or broken glass is added to utilize waste and to assist in initial fusion.

The finely divided raw materials are weighed, mixed, and melted in pot or tank furnaces, depending upon the amount of charge or grade of glass. After melting, forming is done either by hand or automatic blowing, casting, rolling, or molding. These various processes take advantage of the characteristic of glass that it has no definite melting point, but changes its viscosity gradually when going from the liquid to the solid state.

A final, but very important, step in the manufacture of glass is annealing. The process consists of very gradually cooling the heated articles, usually done by carrying the

ware on a conveyor through a heated oven, the so-called "lehr." This slow cooling process is carried out to regulate internal strains which may cause cracking of the piece during use.

The first requisite in a commercial glass is that it not be subject to devitrification; fortunately, glasses that meet this requirement show a large variation in composition. Most commercial glasses contain silica as the chief constituent, and silica or flint glasses possess the important quality of superior resistance to weathering. Silica, incidentally, is the most common and cheapest of the glass-forming materials. Silica itself possesses, in the highest degree, the desirable quality of resistance against weathering and freedom from devitrification, and, if it were not so difficult to melt, it would be the most suitable material for the various uses to which glass is put.

The most widely used glasses are of the soda-lime type, consisting chiefly of lime (CaO), soda (Na_2O), and silica (SiO_2) in the proportions determined primarily by the low ternary eutectic of the system. Soda glass, or "crown glass", of the eutectic composition, however, is too susceptible to weathering and atmospheric conditions, and most soda glasses contain an excess of lime over the eutectic mixture and also additional small amounts of the oxides of magnesium (MgO), aluminum (Al_2O_3), and boron (B_2O_3) to increase chemical stability and to obtain other desirable properties. The so-called "resistance glasses" are modifications of the ordinary crown type but contain more aluminum, boric, or zinc oxides than is usually used in ordinary crown glass.

Another important group of glasses comprises the lead glasses, characterized by the presence of lead oxide, ranging from 20 to 80 per cent. This series of glasses is of great importance in lens design. Lead glasses with very high lead content are used for protective shields against X rays.

Pyrex glass differs from all other types in not being derived in any way from an alkaline heavy oxide, eutectic, but rather from silica glass by the addition of boric and aluminum oxides, with a minimum quantity of alkaline oxide. It is a borosilicate glass and its main characteristics are good mechanical strength, low coefficient of thermal expansion, chemical stability, and good dielectric properties. Pyrex is not the name of one material, as is frequently assumed, but is a trade mark of the Corning Glass Works covering various thermally, electrically, or chemically resistant glasses of different compositions.

Glass insulators are used extensively as pin-mounted line insulators for open-wire lines, and Pyrex glass is especially suitable for such purposes because of its good weathering qualities and resistance against thermal shock. During recent years, glass line insulators have been improved considerably, and the inroads they are making to replace porcelain are noticeable. One advantage of glass, compared with porcelain, is its ability to transmit light. It has been found that an opaque insulator, like porcelain, encourages insects to build nests between pin and insulator, thus providing a current leakage path. For the same reason glass insulators do not heat as much under the light rays of the sun as do porcelain insulators.

Glass, as an electrical insulator, may be found in insulating supports, radio-antenna insulators, radio power-tube bases, capacitor insulation, and line insulators.

For the manufacture of bulbs for incandescent lamps and for electronic tubes, glass must be uniform as to softening temperature and ease of working. The coefficient of expansion must be considered wherever a glass-to-metal seal is applied. Today it is possible to obtain glasses with definite temperature coefficients of expansion within the possible range of glasses, meaning approximately from 2.0 to 10×10^{-6}. This is important for the manufacture of mercury switches, vacuum tubes, and other devices.

One of the most recent technical developments and achievements of the glass industry is the commercial manufacture of *fiber glass*,[18] thus introducing a new insulating material for electrical apparatus. The idea of stretching glass into fibers goes back to antiquity, but only recently has the idea been converted into commercial use. Venetian glass blowers made use of glass fibers for intricate designs on glass ware. The glass blower heated a lump of glass until it became plastic, and his apprentice seized one corner with a pair of tongs and raced away as fast as he could run. Depending upon the speed of the apprentice, a more or less fine fiber was produced. It did not take very long for the apprentice to be replaced by a rotating wheel on which the glass fiber was continuously wound, and our museums contain dresses and other garments made of spun glass during the 17th and 18th centuries.

During the last few years glass companies have undertaken the commercial production of glass fibers and now produce threads with a diameter of 0.0002 inch or about 1/15 the size of the average human hair. They can be spun into thread and woven into cloth. Coarser fibers are used for thermal insulation.

The textile glass fibers are made by two distinct types of manufacture and can be divided into two classes. In each type, glass marbles are fed into small electrically heated furnaces. The molten glass flows by gravity through a row of fine holes in a precious metal die or bushing and comes out as fibers. In order to make these fibers fine, they are either stretched while hot by being wound upon a rapidly rotating drum or they are pulled out into a rapidly descending column of steam which breaks up the fiber into 4- to 8-inch lengths (called staple fiber) and deposits them on a continuously moving belt as a narrow felt or sliver.

The continuous-filament glass produced by the first method may be spun directly into a thread, whereas the sliver of the second method may be reduced in size before spinning; it makes a rougher finish than the continuous thread.

Glass threads may be woven into cloths by using ordinary cotton machinery with slight modifications. Glass textiles look very much like textiles made of rayon or silk. For most electrical uses, the important requisites are good mechanical strength and electrical properties as well as resistance to deterioration from high temperatures and from the action of chemicals, moisture, and dirt. To meet these requirements, special glasses free from alkalies had

to be developed. Alkali-free fiber glass is practically unaffected by moisture or mild alkalies and acids, with the exception of hydrofluoric acid. It is flexible and extremely strong. However, if the fibers are allowed to rub and abrade, they nick and break. This action may be prevented by proper varnish or compound treatment. By coating the fiber with a small amount of oil, fibers can be spun satisfactorily and the resulting fabric does not need any further treatment except for wire insulation which must withstand the severe abrasion often encountered in winding operations.

Fiber-glass structure is porous and can be considered only as a physical spacer unless filled with an organic insulating compound. Treated fiber glass has the desirable characteristic of good dielectric strength and low dielectric constant, but does not possess the voltage breakdown strength of mica tape, particularly after aging at high temperatures. Treated fiber glass is, therefore, vitally dependent on the impregnating compound for dielectric strength and limited in temperature endurance to a range between 125 and 175 degrees centigrade. Treated fiber glass, therefore, should not be exposed to temperatures above the working temperature of its impregnating compound.

MYCALEX

Mica is the most important of mineral insulating materials, but, since the material is used in the natural state without subsequent heating, it cannot be considered as a ceramic material and its description at this place is out of order. Many forms of micas are known to the mineralogists for electrical use; however, only muscovite and phlogopite are of interest. Micas are complex compounds of silica and may be regarded as orthosilicates of aluminum with alkaline metals (potassium, sodium, lithium, and also magnesium, iron, and fluorine). Muscovite is potassium mica; phlogopite is magnesium mica.

Since mica can be obtained only in limited sizes and thicknesses, attempts were made to bond mica flakes with moldable compounds, either of organic or inorganic nature, and compress the mixture, preferably under heat, into a compact mass to desired size and shape.

The best known among mica-compound insulating materials is Mycalex,[15] which is the invention of P. B. Crossley of England and is manufactured in the United States by the General Electric Company. One of the original objects of the invention was to utilize waste mica scraps and dust, and the result was a product having electrical characteristics approaching those of mica and mechanical properties approaching those of metal.

Mycalex is composed of ground mica and lead borate glass. Both these ingredients have high dielectric strength. The materials are prepared in a fine state of division and intimately mixed. For preforming blanks, the material is pressed cold similar to dry-pressing other ceramic materials. The pressed blanks are dried, heated to approximately 700 degrees centigrade in an electric furnace, and finally pressed in an electrically heated mold.

Metal inserts can be molded into Mycalex pieces, which adds greatly to convenience of design and economy in assembly. This is in contrast with the manufacturing procedure for other ceramic products where firing shrinkage and high firing temperatures make it impossible to mold metal inserts directly into insulators. Since Mycalex is never really plastic during forming, only relatively simple designs and metal inserts can be manufactured without unduly increasing the cost.

Another unique feature of Mycalex as a ceramic product is that it can be subjected to all the usual machining operations, such as drilling, filing, sawing, polishing, and punching. Stone-like ceramic materials, such as steatite and porcelain, are too hard to be machined by a metal tool and can only be lapped and ground with the hardest abrasives, like silicon carbide, alundum, or diamond dust. The wear on tools is greater than in ordinary metal-machining processes, and, in some instances, special tools may be required.

Aluminum alloys can be cast around the material without affecting its structure. By this method, fittings can be cast over the ends of rods to form strain insulators, thus eliminating the necessity of machining and fastening the fixture to the insulator.

Two grades of Mycalex are available: a general purpose grade, and a radio grade with low and uniform power-factor characteristics. This latter grade is smoother and less porous. It is the preferred grade where changing atmospheric conditions may adversely affect the electrical insulating properties of other grades of Mycalex.

Mycalex is used in radio apparatus, particularly in radio transmitters, because of its good insulating properties at high frequencies. Specific applications are in high-frequency switches, coil supports, control shafts, and radio antenna insulators.

VITREOUS ENAMELS

Vitreous enamels may be defined as easily fusible silicate substances, consisting of a colorless glass rendered opaque by the addition of metallic oxides and frequently colored by the addition of coloring metal oxides, commonly used in glass manufacture. Vitreous enameled products are used extensively for decorative, protective, and insulating purposes. Their description here is limited, however, to their application as electrical insulators.

Raw materials used in the preparation of enamels are numerous; among the more important ones are: flint, feldspar, borax, cryolite, fluorspar, sodium nitrate, antimony compounds; the oxides of lead, zinc, tin, magnesium, and zirconium; and coloring oxides like those of cobalt, iron, manganese, chromium, nickel, and uranium. The selection of raw materials and their proportions depends on the material to be enameled and the fusion temperature desired. The raw materials are finely ground, mixed together, and melted in a furnace. The liquid melt is poured into water where it freezes to a glass and at the same time breaks up into small shattered glass particles. These glass particles, the so-called "frit" which is not soluble in water, are ground to fine powder and mixed with water and either clay or organic suspension agents to help keep it suspended in water.

Metal parts to be enameled must be free from surface

impurities and are thoroughly washed and treated with acids to remove oxide coatings. Otherwise, good adherence to the surface cannot be assured. On metal parts usually a ground coat is applied first, either by dipping, spraying, or dusting on the dry pulverized enamel composition. After applying the ground coat, the pieces are fired in a furnace at a temperature of approximately 850 degrees centigrade. The ground coat merely provides a suitable layer, the coefficient of expansion of which is between that of the metal part and the top enamel coat. The final enamel coat on top of the ground coat is fired at a somewhat lower temperature than the ground coat.

The enamels are extensively used to cover resistors of the wire-wound core type. For this application, enamels with several properties unusual for most enamels are required. It is important that the thermal coefficient of expansion between ceramic tube, wire, and enamel are close together to minimize crazing of the enamel coating. Furthermore, the enamel must be melted on at a temperature as low as possible to prevent oxidation of the wire and subsequent change of resistance values. Such enamels are usually melted on at a temperature of about 650 degrees centigrade and have a high lead and boron content. The underlying ceramic core may be either vitrified or porous, but must be of such composition that it withstands the rapid temperature changes during enameling and during the use of the resistor.

Another interesting application of enamels is as an insulating coating for the screens in television camera tubes. The insulating material for this purpose should have the following qualifications: It must be inert to the chemical action of the activating agent and have low vapor pressure; it must withstand the temperature encountered in the baking required for outgassing of the tube during exhaust and adhere firmly to the screen without cracking or flaking off during the heating; and, finally, it must have high specific resistance. Special enamels having these properties have been developed for this application.

Competition between ceramic and plastic materials is growing stronger daily, and there is no doubt that certain products made of ceramic materials today will be made of one of the organic plastic materials tomorrow. The art of making organic plastics has advanced during recent years to a greater extent than that of making any other type of insulation. New materials have been brought on the market which are both beautiful and can be molded into most intricate shapes as well as having excellent dielectric properties. This, however, is not discouraging to the ceramic industry and has rather stimulated developments in the inorganic field. Ceramic development and improvements are going on, although not at quite as rapid a pace as in the plastics field.

Two outstanding inventions may be mentioned here which have had rather wide publicity, but are not ready to go into production. The first of these is glass having an extremely low coefficient of expansion and excellent heat resistance. This is a development of the Corning Glass Works and has been discovered during investigation on Pyrex glass. This new glass consists of practically pure silica and has the properties of this material. A glass of Pyrex composition is molded into the desired shape by the well-known methods of forming glass. It is then subjected first to a heat treatment and then to an acid treatment that dissolves all oxides with the exception of silica and leaves silica as a porous skeleton. By a second heating process the porous article is vitrified. The vitrification causes a volume shrinkage of approximately one-fifth of the original size. Bowls made from this new material do not crack when filled with molten lead while resting on a block of ice. The advantages of a material of this type for the electrical industry are obvious. No doubt it will be a valuable addition as a high-frequency insulator.

The second invention is so-called "Alsifilm". This invention originated at the Massachusetts Institute of Technology and consists of the production of a very thin film of ceramic material that can be used in place of mica. Mica is on the list of necessary war materials which must be imported, and a substitute that can be manufactured in the United States would be a very desirable product. Alsifilm is produced by depositing powdered bentonite, a hydrous aluminum silicate, in a very fine state of division on the walls of a centrifuge. The material can be made into sheets of about 0.002 to 0.003 inch thickness, and these sheets are flexible enough so that they can be used in the same manner as natural mica.

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Frequency-Selective Feedback for Audio Systems

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THE performance of the majority of sound systems is limited by the frequency response of the loud-speaker. The frequency distortion inherent in all but the most expensive loud-speaker equipment can be compensated by modifying the gain frequency characteristics of the associated amplifiers by the use of feedback. Not only can the relatively poor frequency response of the average loud-speaker be compensated, but it is possible also to modify the response of a system by this method so that the sound can be reproduced naturally at higher or lower intensity levels.

As a loud-speaker has an irregular frequency response curve, it is practicable to compensate only for general trends in the feedback network, particularly since the humidity and temperature changes often cause the frequency at which a sharp speaker resonance occurs to deviate from its normal value by as much as 20 per cent. The most objectionable resonances cause a decrease in load on the amplifier and a corresponding increase in the voice-coil terminal voltage. At frequencies where these resonances occur, voltage is fed back degeneratively from the voice-coil terminals in order to reduce the effect of the resonances.

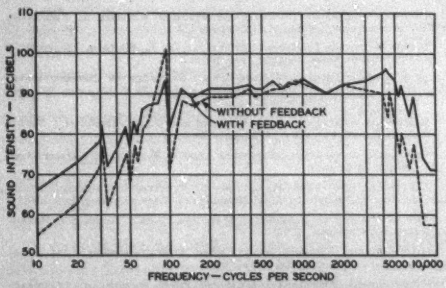

Figure 1. Acoustical response of a typical audio-frequency system with and without frequency-selective feedback; signal input was ten decibels greater when feedback was used

The method, then, consists essentially of using feedback to alter the character of the signal in the electric circuit of the amplifier in such a way as to counteract the undesirable alteration that takes place in the speaker. This is effected, first, by introducing correction in the feedback network for general speaker trends, and, second, by obtaining degenerative feedback voltage from the voice-coil terminals to counteract sharp resonances and wave-form distortion.

Practically, the important factor limiting the compensation is the maximum decrease in the system's useful power output that can be tolerated. In general, if the amplifier itself has a reasonably flat frequency response, the reduction in speaker power output will be about equal to the maximum range of compensation obtained from the feedback. However, this statement applies only to a signal whose power is evenly distributed over the frequency spectrum. Since this condition does not ordinarily obtain in practical applications, the actual reduction in useful power output may be much less than the range of compensation, and for some types of program may be negligible. The reduction of useful power output arises from the fact that the acoustic response of the system can only be flattened electrically by reducing the speaker input at the frequencies where it is most efficient, in order to bring the acoustic output at these frequencies down to what it is at the frequencies where the speaker is less efficient. In other words, the electrical compensation is obtained by reducing power, not by increasing it.

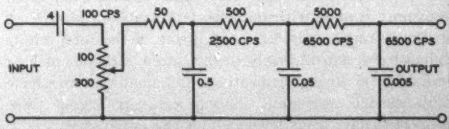

Figure 2. Feed-back network used to achieve the results indicated in figure 1

The network is fed from the voice-coil terminals of the loud-speaker; the output preferably feeds into the grid circuit of the second stage of the amplifier in order to make the amount of feedback independent of the internal impedance of the signal source. All resistance values shown are in ohms and capacitance values in microfarads; cut-off frequencies of the various network sections are indicated in cycles per second (CPS)

Some of the important advantages of this method are:

1. The frequency response of a given system is greatly extended.
2. The variation with intensity level of the frequency response of the human ear can be compensated.
3. A reduction in distortion of wave form by the amplifier or by the speaker takes place at the frequencies where the feedback is degenerative.

Abstracted from a paper "Frequency-Selective Feedback for Improvement of Acoustical Response of an Audio-Frequency Sound System," presented at a student session of the AIEE North Eastern District meeting, Springfield, Mass., May 5, 1939; subsequently awarded, jointly with another paper, the AIEE national prize for Branch paper for the academic year ending June 30, 1939, which award was presented at the Institute's recent 1940 summer convention.

W. N. BROWN, JR., was a student at Massachusetts Institute of Technology, Cambridge, when this paper was prepared; he is now research assistant in the electrical-engineering department of that institution. E. W. SHERIDAN also was a student at MIT when the paper was prepared; he is now connected with RCA Manufacturing Company, Camden, N. J.

4. The mechanical resonances of the speaker are reduced at the frequencies where the feedback is degenerative.

5. The effect of hum and noises not present in the input signal is reduced when they occur at frequencies where the feedback is degenerative.

However, the system has the disadvantage that the ratio of output power to input voltage is less with feedback than without feedback; furthermore, the maximum useful output power is less with feedback than without feedback. Moreover, distortion of wave form is accentuated at frequencies where feedback is positive. These disadvantages are not of very great importance in most practical cases.

An Electronic Relay for Initiating Vapor Discharges

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THE recent introduction of low-voltage fluorescent lamps has created a need for automatic control auxiliaries. Several methods have been devised for the automatic starting and operation of these lamps, the most recent being a device known as the "glow relay".* Earlier methods had certain disadvantages as to cost, effect on the lamps, circuit efficiency, dependability, and ease of wiring. The invention of the glow relay resulted from attempts to overcome these undesirable features.

The relay is essentially a small glow-discharge lamp, comprised of two electrodes in a glass envelope containing neon. The container is about the size of an automobile headlight lamp. One of the electrodes is constructed of a heat-sensitive bimetallic strip with a contact member at its extremity. The other electrode is a projecting wire placed so that it will touch the contact member when the bimetallic strip flexes due to heating.

When a gaseous glow discharge takes place in this device, the bimetallic strip is heated by positive-ion bombardment and flexes so that the contacts are closed. When the contacts make an electrical connection, the glow discharge is short-circuited. The device is designed to have a breakdown voltage of about 90 to 100 volts. This relay, labeled *R*, is connected in the fluorescent lamp circuit as shown in figure 1.

When the control switch *S* is closed, line voltage of say 110 volts is applied to the relay through the lamp electrodes *D* and *E* and the current-limiting reactor *B*. The line voltage causes breakdown of the neon in the relay, and a glow-discharge ensues. The bimetallic strip then becomes heated; it flexes and causes the contacts to engage, short-circuiting the glow, and permitting electrode-heating current to flow in the lamp. After the glow-discharge is short-circuited, the bimetallic strip cools and the contacts subsequently open, breaking the circuit and causing a high voltage to be induced in the series inductance. This high voltage is of sufficient magnitude to insure definite initiation of the mercury-vapor discharge of the lamp.

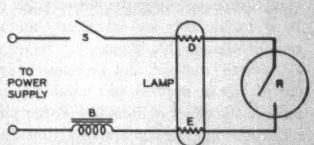

Figure 1. Schematic diagram showing how relay is connected to low-voltage fluorescent lamp

After initiation of the discharge, the lamp begins to operate and its terminal voltage drops to about 60 volts. This voltage also is applied to the relay, but is insufficient for the formation of another glow-discharge in the relay, thus preventing further operation of the relay while the lamp is operating.

The glow relay has many advantages over previous fluorescent-lamp automatic-starting devices. In breaking the electrode heating current it causes voltages to be induced in the reactor which insure positive breakdown of the lamp. The device does not operate and consume power once it has started the fluorescent lamp; consequently the circuit efficiency is not affected by its presence. It has but two electrical connections, thus permitting a simplicity of wiring. The relay has exceedingly long life. In an actual test, one relay has started fluorescent lamps over 1,000,000 times. The relay is not sensitive to changes in room temperature; it does not hum; it is inexpensive and compact. In starting and restarting a lamp after a power interruption, it acts quickly and effectively. In addition, it may be stated that the relay, although first developed for use with fluorescent lamps, is not limited to use with these particular lamps. It may find application in the automatic control of other discharge devices of the same nature which exhibit the same phenomena.

Abstracted from a paper "The 'Glo-Relay', A New Method of Initiating Vapor Discharges," presented at a student session of the AIEE North Eastern District meeting, Springfield, Mass., May 5, 1939; subsequently awarded, jointly with another paper, the AIEE national prize for Branch paper for the academic year ending June 30, 1939, which award was presented at the Institute's recent 1940 summer convention.

EDWARD C. DENCH was a student at Worcester Polytechnic Institute, Worcester, Mass., at the time this paper was prepared; he is now affiliated with Interchemical Corporation Research Laboratories, New York, N. Y.

* The Westinghouse "glow relay" was invented by the author during summer-vacation work for the engineering laboratories, lamp division, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J. Further development work, bringing the relay to its present form, is credited to the members of the vapor lamp development department of that company under the direction of D. S. Gustin.

A Graphical Solution of Transient Stability

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An extension of the equal-area method of determining transient stability limits, applicable to power systems that can be reduced to two equivalent machines

THE equal-area method gives a simple criterion for the determination of transient stability of a power system in which the synchronous machinery can be reduced to two equivalent machines, but it alone is not adequate when switching or other secondary disturbances of the system follow the initial disturbance. The method here proposed is an extension of the equal-area method. Its advantage lies in the fact that it gives angular position of the synchronous machine as a function of time; it gives, in other words, a swing curve. It thereby permits the general method of the equal-area solution to be applied to system disturbances in which time is a factor. It can be used, for example, to study switching operations following a fault.

The proposed method is essentially one of graphical integration, based upon the power-angle curve of the system. It is considerably less laborious than a step-by-step solution of comparable accuracy. It is restricted, as is the equal-area method, to systems to which power-angle curves can be applied, but unlike the latter it will readily include the effect of damping (either positive- or negative-sequence damping), governor action, and other effects that are functions of time or velocity. Change of flux linkages within the synchronous machines can be introduced into the solution with a fair degree of approximation if desired. Accuracy of computation by this method has been checked experimentally, and also by comparison with other methods.

THEORY

The power input to a synchronous machine is consumed in three ways: power output, power consumed in damper windings and other losses, and power used in accelerating the rotating part of the machine (this may be either positive or negative) thereby altering its kinetic energy.[1] Denoting the difference between power input and output by ΔP:

$$P_i - P_o = \Delta P = P_d + P_a \tag{1}$$

(All notation is tabulated at the end of the article.) Neglecting damping, for simplicity in this introductory discussion:

$$\Delta P = P_a \tag{2}$$

The power that produces acceleration of the rotating machine is equal to the product of the torque that produces acceleration and the angular velocity of the machine:

$$P_a = \omega T_a \tag{3}$$

During any transient disturbance from which recovery of synchronism of the system is to be expected, ω does not vary more than a few per cent from synchronous angular velocity. It is therefore approximately correct to write:

$$P_a = \omega_s T_a \tag{4}$$

In these equations, T_a is the product of the angular acceleration of the machine and its moment of inertia:

$$T_a = \alpha I = \frac{d\omega}{dt} I \tag{5}$$

The angular velocity at any instant may be considered to have two components, one the normal synchronous velocity, and the other the velocity due to the transient disturbance:

$$\omega = \omega_s + \Delta\omega \tag{6}$$

from which it follows that:

$$\alpha = \frac{d\omega}{dt} = \frac{d(\omega_s + \Delta\omega)}{dt} = \frac{d(\Delta\omega)}{dt} \tag{7}$$

The angular position of the rotor of the machine, θ, changes because of both the synchronous component of velocity and the incremental velocity produced by the transient disturbance:

$$\theta = \theta_s + \Delta\theta \tag{8}$$

and since

$$\omega = \frac{d\theta}{dt} \tag{9}$$

it follows that

$$d(\Delta\theta) = (\Delta\omega)dt \tag{10}$$

The angle δ is the power angle of the machine (this is common usage). It differs from the angle $\Delta\theta$ in the foregoing discussion by a constant angle: When the machine is in its steady running position, before a transient disturbance occurs, $\Delta\theta = 0$, while $\delta = \delta_o$. Therefore

$$\Delta\theta = \delta - \delta_o \tag{11}$$

Now consider the integral

$$\int_{\delta_o}^{\delta} P_a d\delta = \int_{o}^{\Delta\theta} P_a d(\Delta\theta) \tag{12}$$

Substituting into this equations 4, 5, 7, and 10:

$$\int_{\delta_o}^{\delta} P_a d\delta = \omega_s I \int_{o}^{\Delta\omega} (\Delta\omega) d(\Delta\omega) = \omega_s I \frac{(\Delta\omega)^2}{2} \tag{13}$$

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1. For numbered references see list at end of article.

The product $\omega_s I$, an inertia constant of the machine, hereinafter is designated by G; that is, $G=\omega_s I$ (further discussion of this quantity is given in the discussion of "Units"). Introducing this symbol, equation 13 gives:

$$\Delta\omega=\sqrt{\frac{2}{G}\int_{\delta_o}^{\delta}P_a d\delta} \tag{14}$$

From equation 10:

$$dt=\frac{d(\Delta\delta)}{\Delta\omega}=\frac{d\delta}{\Delta\omega} \tag{15}$$

Integrating, and substituting equation 14, finally gives:

$$t=\sqrt{\frac{G}{2}}\int_{\delta_o}^{\delta}\frac{d\delta}{\sqrt{\int_{\delta_o}^{\delta}P_a d\delta}} \tag{16}$$

Evaluation of this integral gives angle as a function of time (implicit) which is the solution of the problem under consideration, being a "swing curve."

If analytical solution of this integral were practicable, graphical methods would be unnecessary. But analytical solution is possible in special cases only. One simple solution, which will be found useful as part of the graphical method, can be obtained by making the assumption that P_a is constant, and not a function of δ. Then

$$t=\sqrt{\frac{G}{2P_a}}\int_{\delta_o}^{\delta_1}\frac{d\delta}{\sqrt{\delta}}=\sqrt{\frac{2G(\delta_1-\delta_o)}{P_a}} \tag{17}$$

But for general determination of swing curves the integrals of equation 16 are evaluated graphically.

APPLICATION OF METHOD

In applying the graphical method, one begins with the power-angle curve. Consider, specifically, a generator feeding an infinite bus through a transmission line. As a result of some disturbance of the system, such as the sudden occurrence of a fault on the transmission line, the power output of the generator becomes less than the power supplied to the generator by the prime mover. The power-angle curve of the system under transient conditions is shown in figure 1*a*; at each instant the angle δ and the power output P are related by the curve shown.

At the instant of the disturbance the angular position of the machine is known to be δ_o, so the power output of the machine immediately following the disturbance will be P_o.

The difference between the power output, P, and the power input, P_i (which is here assumed to be constant), is ΔP, and the vertical lines of shading may be interpreted as representing values of ΔP at different angular positions. Damping will be neglected in the present discussion, so ΔP will also be the accelerating power, P_a.

Area in the power-angle diagram represents the product of power and angle, and the shaded area is therefore the integral of equation 12. This area is next plotted, as in figure 1*b*. Area of the shaded part of figure 1*a* is measured (most readily by a planimeter), and beginning with zero area at δ_o one plots in figure 1*b* the accumulated area as one passes from left to right. Area below P_i is positive and that above P_i is negative. The accumulated area is designated A, as in figure 1*b*. The value of A at each value of δ in figure 1*b* is now multiplied by $2/G$ and the square root found; the result is plotted in figure 1*c*, which is a curve of the velocity of swing of the machine (see equation 14).

The next step is to plot the quantity $1/(\Delta\omega)$, as in figure 1*d*, taking reciprocals of values of curve 1*c* for each value of δ. Area under this curve, measured from left to right (again using a planimeter) and plotted as in figure 1*e*, is the required swing curve of the machine.

In practical computation it is not necessary that all these curves be drawn. Curve *b* may be omitted, and commonly (depending on whether damping and governor action are to be considered) curve *c* may be omitted also. If the power-angle curve is of such simple form (for example, sinusoidal) that the velocity of swing, $\Delta\omega$, can be found by ordinary integration in equation 14, curve *d* can be computed without the necessity of drawing curves *a*, *b*, and *c*, and graphical integration of curve *d* to obtain the swing curve *e* completes the solution.

In finding the area under curve *d*, difficulty is encountered in measuring area near the beginning and end of the swing. This is because the value of $1/(\Delta\omega)$ becomes large without limit as δ approaches δ_o, although the area under the curve is nevertheless finite. To avoid this difficulty it is safe to assume that during the first short interval of time the value of P_a does not vary from its value at the first instant. The time required for the machine to swing through some arbitrarily selected small angle to an angle δ_1 is then given by equation 17. For convenience, the solution of equation 17 is given graphically in figure 2. Its use is illustrated in the following example.

EXAMPLE

In this example the solution is carried out in its simplest form, assuming constant flux linkages and neglecting damping and variation of input power.

A generator feeds power to an infinite bus through two transmission lines in parallel; a three-phase fault occurs on one line which is automatically disconnected from the system after 0.20 second. (This is example III, page 427, reference 1.) The following information is given or is readily computed:

Power input, $P_i=0.80 \quad \delta_o=18.1$ degrees

Power-angle curves are (assume $x_d'=x_q'=x_q$):

During fault $\quad P=0.936 \sin\delta$
After clearing $\quad P=2.06 \sin\delta$

Inertia constant, $G=2.56\times10^{-4}$ seconds^2 per electrical degree.

Solution. Referring to figure 1, curves *a*, *b*, and *c* are not needed because A, and therefore $\Delta\omega$, are readily computed as follows. During fault:

$$P_a=P_i-P=0.80-0.936\sin\delta$$

$$A=\int_{18.1^\circ}^{\delta}P_a d\delta=0.80\delta+53.6\cos\delta-65.5$$

(δ is here integrated in degrees, not radians)

$$\frac{1}{\Delta\omega}=\sqrt{\frac{2.56\times10^{-4}}{2A}}$$

This is computed and the result is plotted as curve D in figure 3. Area to the left of this curve, the orientation being different from that of figure 1*d*, represents time. Area is measured and time is plotted as curve A, except that the first value of time, at 20 degrees, is obtained from figure 2 as follows:

$\delta_1 - \delta_0 = 20.0 - 18.1 = 1.9$ degrees

P_a at 18.1 degrees $= 0.509$

$$\sqrt{\frac{G}{P_a}} = \sqrt{\frac{2.56 \times 10^{-4}}{0.509}} = 0.022$$

Using this value to enter the chart of figure 2, and interpolating between diagonal lines for a swing of 1.9 degrees, one finds that the time required for this swing, and therefore the time required to reach an angular position of 20.0 degrees, is 0.042 second. This point is plotted as the first point on curve A, figure 3, and graphical integration is then used to determine other points on the curve until it is found that total elapsed time equals 0.20 second. This is the time at which the fault is cleared, and a different power-angle curve is thereafter used. It is found that when time $= 0.20$ second, $\delta = 51.0$ degrees, and $A = 9.10$.

After clearing the fault:

$P_a = 0.80 - 2.06 \sin \delta$

Total area, including area before clearing the fault, is:

$$A = 9.10 + \int_{81.6^\circ}^{\delta} P_a d\delta = 0.80\delta + 118.2 \cos \delta - 106.2$$

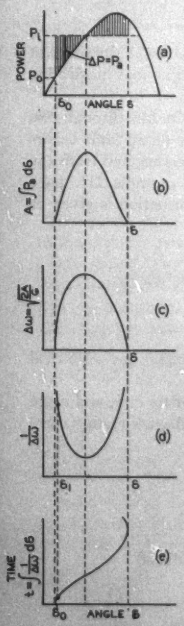


Figure 1 (left). Steps of a typical graphical solution

Then $1/(\Delta\omega)$ is computed from the same formula as before, but using the revised value for A, and the results are plotted as curve E of figure 3. Graphical integration is then continued by measuring area to the left of this curve, and the resulting values of time are plotted as points on curve A. Graphical integration is impracticable beyond 60 degrees. It was found in computing A that it becomes zero at 61.0 degrees, and this establishes the angle of maximum swing. The chart of figure 2 is again used:

From 60.0 to 61.0 degrees, swing $= 1.0$ degree

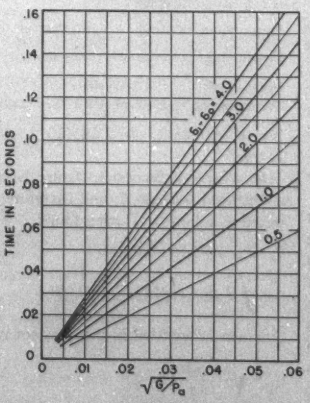
At (average) 60.5 degrees, $P_a = 0.99$ and $\sqrt{G/P_a} = 0.0161$

From figure 2, time to swing from 60.0 to 61.0 degrees $= 0.022$ second

Since it was previously found that the time at 60.0 degrees was 0.252 second, addition gives the time at 61.0 degrees as 0.274 second. Beyond this time the curve is found by symmetry until the angle at which the fault was cleared is again reached. For later times the graphical method can be continued, using an extension of curve E, if desired.

Swing curves computed by the point-by-point method are included in figure 3 for comparison. The graphical solution is free from the cumulative error of the point-by-point solution which is particularly apparent in curve C, and the labor required is much less than for the point-by-point solution with short steps as illustrated by curve B.

Figure 2

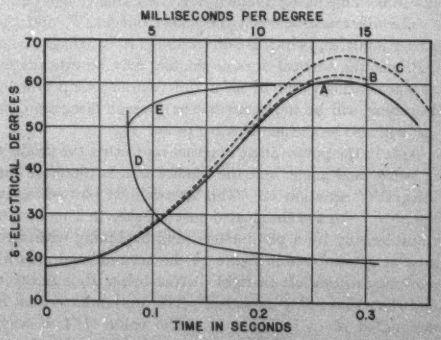


NOTATION

A	area on power-angle curve sheet.
G	inertia constant.
I	moment of inertia.
P	power.
P_a	power used in accelerating the machine.
P_d	power absorbed in damping.
P_i	power input.
P_o	power output.
T_a	torque used in accelerating the machine.
t	time.
α	angular acceleration.
Δ	a symbol meaning "transient increment of."
ΔP	difference between power input and power output.
$\Delta\theta$	angle of transient swing from synchronous position.
$\Delta\omega$	angular velocity of transient swing.
δ	angle of swing from direct axis.

Figure 3. Example of computed swing curve

A—Computed by graphical method
B—Computed by point-by-point method using 0.01-second steps
C—Computed by point-by-point method using 0.05-second steps
D, E—Reciprocal-of-velocity curves (upper scale)



δ_0 steady value of δ preceding transient disturbance.
θ angular position.
θ_s synchronous angular position; that is, position the machine would have attained at synchronous speed had there been no transient disturbance.
ω angular velocity.
ω_s synchronous angular velocity.

UNITS

Any consistent system of units may of course be used, but the following is recommended:

Angle in electrical degrees.

Time in seconds.

Angular velocity in electrical degrees per second.

Power in fraction of rated power (per-unit system).

Area. For plotting figure 1*b*, unit ordinate corresponds to unit area on figure 1*a*. It is convenient to consider unit area a rectangle 10 electrical degrees by 0.1 (per unit) power. For plotting figure 1*e*, unit area on figure 1*d* represents one second. It is convenient to consider 0.01 second equivalent to a rectangle 10 electrical degrees by 0.001 on the reciprocal-of-velocity scale.

Inertia constant, G, in (seconds)^2 per electrical degree (this is the reciprocal of the unit of angular acceleration, and makes possible the simple formula: $\alpha = \Delta P/G$). The value of G is found from:

$$G = \frac{1.28I\ (\text{rpm})^2\ 10^{-9}}{(\text{rated kva})(\text{frequency})} = \frac{H}{180\ (\text{frequency})} = \frac{M}{(\text{rated kva})}$$

where I is moment of inertia in (pound)(feet)^2 and M and H are different inertia constants from references 1 and 3, respectively.

CONCLUSION

A method of graphical computation of swing curves of synchronous machines under transient conditions has been outlined. Its theoretical basis is related to that of the "equal-area criterion" of transient stability. It gives angular position as a function of elapsed time, however, which is usually a necessary addition to the information obtained from the equal-area criterion.

The method is capable of taking into account system loads, losses, saliency of poles, damping, and other factors that are frequently decisive in stability studies. Its use is limited to systems to which power-angle curves are applicable. The method is relatively easy to use and is accurate.

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2. Symmetrical Components, C. F. Wagner and R. D. Evans. McGraw-Hill Book Company, Inc., New York, 1933.
3. First Report of Power System Stability. AIEE Transactions, volume 56, 1937, pages 261–82.
4. System Stability as a Design Problem, R. H. Park and E. H. Banker. AIEE Transactions, volume 48, 1929, pages 170–94.

For other references see bibliography of reference 3.

Conowingo (Md.) dam and power plant on the Susquehanna River, which supplies a major portion of the power used in Philadelphia, Pa., is on the inspection-trips schedule of the AIEE winter convention to be held in that city January 27–31, 1941

Institute Activities

Middle Eastern District Sets Record With Cincinnati Meeting

THE Cincinnati Section was host to a very successful three-day meeting of the Middle Eastern District held October 9–11, with headquarters in Cincinnati's Netherland Plaza Hotel. With a verified registration of 599 members, guests, and students the meeting established a new high record for the District, and one exceeded only by District 3 at New York in 1926 (700), and by District 5 at Chicago in 1927 (900) and in 1929 (600) among the 42 Institute District meetings that have been held since they were inaugurated in 1924.

GENERAL MEETING

The meeting was opened by E. S. Fields, chairman of the general committee who introduced C. T. Sinclair, vice-president for the Middle Eastern District. Vice-President Sinclair complimented Chairman Fields and his committee for the excellence of the program, and President Sorensen spoke briefly. A most cordial welcome to the meeting was extended by Mayor James Garfield Stewart of Cincinnati. The Mayor gave a good insight into the early history and traditions of the city as well as its friendly community spirit and said that it was "fine to have here men who have the American ways of doing things and that made one optimistic for the future.... I am delighted to see competitive people get together and work out their problems co-operatively in a friendly manner."

MEETING LUNCHEON

The meeting luncheon was held on Thursday, October 10, in the Pavilion Caprice Terrace. Vice-President Sinclair expressed his personal gratification for the large attendance and commented on the high quality of the papers and discussions. President Sorensen addressed the luncheon meeting briefly concerning some of the broader aspects of engineering in relation to preparedness and the public at large. He referred to the inventions of the cotton gin, the harvester, the automobile, and the radio, emphasizing that industry is the real backbone of preparedness and that engineers long have been intimately associated with the development of industry. President Sorensen urged engineers to "stretch outside of the professional societies a bit more and get into civic and community activities, such as the Chamber of Commerce, etc., in order to become better acquainted with people from other walks of life." Thus engineers would be in a better position to help in the solution of problems having social implications.

STUDENT ACTIVITIES

In the opinion of those responsible for student activities at the Cincinnati meeting, the student attendance and participation "was the outstanding feature in view of the distances involved in traveling to Cincinnati." Of the 22 student branches in the District, the registration included representatives from 18, 17 of them outside of Cincinnati. In addition to the Enrolled Students affiliated with the Institute, many other engineering students are reported as being in attendance, appearing in the registration figures as men guests.

There was no technical program of student papers, as the branches in the District had voted against such a program last spring. However, the items of interest in the regular program of technical sessions were described as being so diverse in character and so numerous in quantity that the students were very well served and were outspoken in their praise. There were special inspection trips and entertainment for students, and free transportation for trips to a steel mill and a rolling mill. Also, students participated in the regular inspection trips.

Analysis of Registration at Cincinnati

Classification	Location: Cincinnati Section	District 2*	Other Districts	Totals
Members	97	105	79	281
Enrolled Students	31	48	4	83
Men Guests	113	38	32	183
Women Guests	24	19	9	52
Totals	265	210	124	599

* Outside Cincinnati.

The meeting of Student Branch counselors, with Chairman L. R. Culver of the District's committee on student activities presiding, was held at 10 o'clock Thursday morning, October 10, with 18 of the District's 22 student branches represented. Invited guest speakers were Professor H. W. Bibber and Doctor F. C. Caldwell, both of Ohio State University, Columbus. The business session of the conference was devoted primarily to consideration of the question of District prize papers and related awards. The counselors completed their two-year study of this subject, and forwarded their recommendations to the District executive committee. The counselors concluded their session by selecting the University of Maryland for next year's conference, and electing Professor H. S. Bueche (Villanova) as chairman of the District committee on student activities for the ensuing period.

In parallel with the counselors' meeting, the student officers group held a meeting with Chairman John P. Quitter of the University of Cincinnati Branch presiding. This group consisted of 25 people from 18 schools. Pursuant to a review of recent experience, and a general discussion of the topic, the branch officers decided to continue for the coming year the Middle Eastern District "Student News-Sheet" which was started in 1939. On the strength of its fine performance of last year, the Case School of Applied Science Branch was successfully prevailed upon to continue as publishing agent for the ensuing year. All Branches will contribute news items, and each Branch will receive four copies of each issue at a yearly cost of $2.00 per Branch.

At noon the students and counselors luncheon was held and the gathering was addressed by Vice-President C. T. Sinclair.

DISTRICT EXECUTIVE COMMITTEE MEETING

The annual meeting of the Middle Eastern District's executive committee was held at 2:00 p.m., Thursday, October 10. Among the items of business it was decided to hold the next meeting of the Middle Eastern District at Pittsburgh in 1942. W. B. Morton, secretary of Philadelphia Section and vice-chairman of the 1941 winter convention committee, was chosen as the District's delegate to the national nominating committee.

ENTERTAINMENT AND TRIPS

The informal dinner was held in the Pavilion Caprice at the Netherland Plaza Hotel on Thursday evening, October 10, with music and dancing between courses. Members and guests were entertained with stories told by President Sorensen resulting from his experiences while traveling east from California by train. An entertaining and instructive satire on the subject of "The Passion for Painless Education" was given by Doctor Frank W. Chandler, professor of English at the University of Cincinnati. The talk was humorously exemplified by typical magazine advertisements. Professor A.M.Wilson acted as toastmaster. After the talks guests were entertained with excellent musical and dancing acts.

A smoker and buffet dinner were held in the ballroom of the Hotel Metropole on Wednesday evening. Following the dinner,

Middle Eastern District Meeting Attendance 1925–40

Date	Location	Attendance
1940—Oct. 9–11	Cincinnati, Ohio	599
1939—Oct. 11–13	Scranton, Pa.	313
1937—Oct. 13–15	Akron, Ohio	464
1932—Oct. 10–13	Baltimore, Md.	240
1931—Mar. 11–13	Pittsburgh, Pa.	500
1930—Oct. 13–15	Philadelphia, Pa.	500
1929—Mar. 20–23	Cincinnati, Ohio	270
1928—Apr. 17–20	Baltimore, Md.	400
1927—Apr. 21–23	Bethlehem, Pa.	400
1926—Mar. 18–19	Cleveland, Ohio	430
1925—Jan. 23–24	Washington, D. C.	212

entertainment and smokes were offered.

Thursday afternoon a number of the people attending the meeting took advantage of the popular trip to the Newport Rolling Mills and to the Andrews Steel Company at Newport, Kentucky, as well as the alternate sightseeing tour of Cincinnati and its environs. Those taking the latter trip enjoyed the privilege of visiting the new central fire signal control station of the Cincinnati Fire Department. These trips were also repeated on Friday afternoon, at which time there were other trips to the studios and transmitter of Station WLW and the Crosley Television Station as well as the Columbia Station of the Cincinnati Gas and Electric Company. During the meeting women guests were entertained by a series of special events including a bridge-luncheon, a shopping and sightseeing tour, a visit to a radio studio to witness the broadcasting of a national feature program. Trips were taken to nearby industries, and to the Charles Phelps Taft Museum where a musicale and tea were enjoyed.

TECHNICAL SESSIONS

Parallel technical sessions held on each of the three days during the meeting were well attended and offered a variety of subject matter. The session on aviation, instruments and control, as well as the session on industrial power applications and the conference on protective lighting, were considered as initial steps to acquaint engineers with some of the problems of national defense. The papers were presented by officers in the United States Army Air Corps, as well as by men in industries co-operating in the defense program. The session on aviation, instruments and control was presided over by E. E. Minor, Baltimore, chairman of the Institute's newly-formed committee on air transportation. Chairmen for the other sessions were: C. F. Lee, Cincinnati, general; E. W. Oesterreich, Pittsburgh, power transmission and distribution; C. M. Gilt, New York, electrical machinery; J. J. Orr, New York, industrial power applications; O. P. Cleaver, Bloomfield, N. J., conference on protective lighting; E. E. Dreese, Columbus, Ohio, selected subjects; J. L. Hamilton, St. Louis, Mo., session on single-phase motors and conference on motors and applications. Attendance at the nine technical sessions and conferences ranged from 55 to some 240, averaging about 115.

Conferences on Lighting and Motors Held in Cincinnati at District Meeting

TWO technical conferences were held as a part of the regular program of the Middle Eastern District meeting held in Cincinnati, Ohio, October 9–11, 1940. High lights of these conferences are reflected in the following items as reported by Chairman O. P. Cleaver of the Conference on Protective Lighting, and by Chairman J. L. Hamilton of the Conference on Motors and Applications.

Conference on Protective Lighting

This conference was organized for the purpose of discussing the need and the present-day methods of lighting industrial plants as a protective measure against espionage and sabotage. Four informal papers were given followed by considerable discussion from the audience.

In the first paper, by Mr. Suran of the Federal Bureau of Investigation, it was pointed out that the need for protective lighting has increased greatly in the last few months. The FBI has been appointed by the President of the United States to undertake all matters pertaining to sabotage and similar "Fifth Column" activities. Already, the special agents of this Department have investigated many important factories and where necessary have recommended protective lighting along with other types of protection.

It was pointed out that the FBI had no authority to force plant officials to install protective lighting, nor did they set up standards to govern the extent of this lighting and the methods used. Their function is solely to advise of the need for this type of protection.

A significant point was made by Mr. Suran to the effect that it was advisable to have sufficient outdoor and indoor lighting to enable guards not only to see the intruder but to recognize him as well. Since present protective lighting standards are far below that needed for actual recognition, it was evident that changes would have to be made in standards if this program were carried out. The questions following Mr. Suran's talk brought out the fact that lighting is essential, especially in factories where guard forces are inadequate. It was stated that adequate lighting might be considered to take the place of guards if an adequate protective guard force was prohibitive in cost.

Elaborating more specifically on the need for protective lighting, Mr. Summers, the next speaker, pointed out that two problems were involved: (1) protective lighting before invasion of the premises; and (2) protective lighting after invasion. In the first case, as much light as possible is an advantage. In the second instance, as little light as possible can be an advantage. Light in itself cannot keep the saboteur out, according to Mr. Summers, but will keep out the minor criminals and cranks.

According to Mr. Summers, guards should not be kept in the dark unless placed on the roof where they have a certain measure of safety and yet can survey the entire property. Glare is an important protection factor for guards when properly used. If floodlights are directed toward a possible intruder, the glare will serve to blind him and obscure the guard. Shadows are dangerous and should be avoided in any type of protective lighting.

The following elements of a plant need particular study in designing protective lighting:

1. An adequate fence around the property should never be omitted as a protective element. It should be painted white or have a light background.
2. Dark alleys should be well lighted, particularly if near railroads or highways.
3. Parked railway cars should be well lighted, for they are good places for saboteurs to hide.
4. All entrances and exits should be lighted whether used at nighttime or not.
5. Accessible roofs, where intruders might possibly jump from another building outside on to the property should be protected.
6. Dead-end streets and blind approaches should be kept in mind.
7. Wharves and approaches from water require special attention.
8. Generating stations should not be floodlighted, but should have light surrounding the station. Floodlighting of important buildings, such as this, draws attention to their importance, Mr. Summers pointed out.

The use of dogs as a supplement to lighting was stressed several times during the conference. It was pointed out that they are very effective in searching out intruders and are an inexpensive method of protection.

The next speaker, Mr. Steiner, discussed more in detail the types of lighting available to meet protective lighting specifications. On a large pictorial representation of a typical factory and surrounding area, he pointed out that the boundaries should be given first attention. Two methods for lighting the boundaries were discussed:

First, the use of floodlights with spread lenses mounted two to a group, placed on the inside of the property and directed outward. This method uses glare as a hindrance to a possible intruder.

The second method is to mount floodlights along the fence on poles or structures near the fence. The speaker preferred the method of lighting in two directions from each pole, rather than a uni-directional method. Poles should be from 25 to 30 feet high and spaced some 300 feet apart, with 500-watt narrow-beam floodlights for the best results. He pointed out that a less expensive and yet effective method is the use of street-lighting types of units suspended from poles about 25 feet from the ground. For this purpose, 300- to 500-watt lamps on 75- to 125-foot spacing were recommended.

Unfenced boundaries such as docks and water approaches also should be given consideration. Floodlights with spread lenses, set back and aimed out over the water, seem to be the best method suggested to date.

Two types of entrances to a plant were emphasized by Mr. Steiner: (1) authorized entrances where the lighting should be sufficient to recognize anyone passing through or approaching; (2) unauthorized entrances, such as a railroad track or a stream running through the property. The latter type should be very carefully illuminated in a manner to prevent dense shadows where intruders may easily conceal themselves.

On the inside of the boundary, the lighting must be of such a nature as not to spotlight power houses, office buildings, storage tanks, etc., but rather to light the area around them. Floodlighting was recommended. Poles located on the grounds or mountings along the tops of buildings seem to provide the most favorable locations for such floodlights. Wherever possible, a band of light around a building, directed in such a manner that the glare from the lighting units would work to the disadvantage of an intruder and to the advantage of any guard, is the most desirable kind.

In addition to general area lighting and boundary lighting, it is important that a separate system of emergency lighting be available in case power supply lines are cut or otherwise destroyed. This system could be portable or housed in a special tower containing manually-operated searchlights, so mounted that they could be directed to any spot on the factory grounds that might be in danger from saboteurs. Gasoline-engine-driven generating plants were preferred, although storage batteries might possibly be used for such an emergency system.

The last paper of the afternoon was by Mr. Dana, who discussed the various types of floodlights available for protective lighting purposes. He illustrated his talk by demonstrating types of equipment now available.

In addition, he discussed types of circuits and controls for protective lighting, favoring the multiple circuit controlled locally by a manual switch as being generally the most economical. Time switches and photo-electric controls are serviceable, but more expensive. In boundary lighting, however, the series circuit with constant-current transformers seems to be the most serviceable type of distribution. He pointed out that the tendency today is to replace the old metallic type of cable with cheaper rubber-insulated cable covered with a very tough coating.

Types of light sources also were discussed briefly as to their relative merit and cost, with the incandescent lamp being the favorite at present because of its inexpensiveness and serviceability. It was pointed out that high-intensity mercury lamps require some time to relight after a circuit is disturbed when the lamp is hot and, furthermore are rather sensitive to voltage variations. The sodium lamp has possibilities, but it also has the time-lag factor to overcome in starting, and the extended light-source made reflector control less accurate.

Following the papers, there was considerable discussion from the audience. Emphasis was given to the necessity for easy maintenance and quick replacement of lamps and fixtures when injured. Cost figures were given to show the comparative cost of a specific installation of protective lighting, using incandescent, sodium, and high-intensity mercury vapor lamps. The incandescent lamp proved to be the least expensive, provided current rates were less than one cent per kilowatt-hour.

Conference on Motors and Applications

This conference was held Friday afternoon, October 11. The fore part of the conference session was devoted to a continuation of the discussion of the seven technical papers presented at the Friday morning regular technical session on the general subject of single-phase motors. Subsequently E. L. Splitstone, chief engineer of the Emerson Electric and Manufacturing Company, St. Louis, Mo., presented an informal paper concerning "Uses and Abuses of Thermal Protectors." Speaking concerning the application rather than the types or construction of such devices, Mr. Splitstone pointed out that a protection device actuated only by current is not entirely adequate for small motors, especially motors of the induction type. Such motors normally have starting currents quite high in comparison with their full load current. Hence, if the fuse, breaker, or relay, even though of the time-element type, has sufficient capacity-to permit starting under load conditions, it probably will permit continuous overloading sufficient to overheat or burn out the running windings. The speaker considered that the inherent overheating protector appears to be the answer to this problem, but that it is in danger of being condemned or at least of having its use restricted because of misuse or improper application. The speaker therefore considered that it was desirable for the motor manufacturing industry to join in giving the problem the attention required to assure that the advantages of the thermal protector may be preserved to the industry and to assure that its use will not be condemned because of improper application or usage.

The discussion, in general, agreed with the thoughts expressed in Mr. Splitstone's paper and all felt that while the inherent thermal protectors are proving very beneficial, especially in the protection of small motors, there are opportunities for the abuse of motors through the use of inherent protectors under some conditions of operation, and that all must co-operate in safeguarding the interests of both the motor manufacturer and the user.

Mr. Hough of the Reliance Electric & Manufacturing Company, Cleveland, then presented an informal paper entitled, "Recent Developments in Magnet Wire." Mr. Hough gave the result of extensive research on new developments in magnet wire, including wire coated with nylon, formex, and formvar, as well as the conventional enamel and cotton coverings. Mr. Hough pointed out that these new magnet-wire insulating materials are being used to an appreciable extent; that the quality of these new materials is improving, and the knowledge and ability of the manufacturer to apply the insulation and use the materials also is improving.

He cautioned against the industry proceeding too rapidly in the use of these new materials. An interesting and informal discussion by several of those present indicated that, in the main, all were in agreement with the conclusions reached by Mr. Hough.

National • • • •

Plans Progressing for Winter Convention in Philadelphia

Plans have been under way for nearly a year for the forthcoming 1941 winter convention in Philadelphia, Pa., January 27–31, 1941. The "Quaker City" with its numerous industries of a highly diversified nature and its historical background offers many attractions for visitors. Full advantage of these features will be taken by the winter convention committee in making arrangements for the meeting. Tentative plans call for a larger number of technical sessions than heretofore and for some of the inspection trips and sessions to be co-ordinated. Convention headquarters will be in the Bellevue-Stratford Hotel.

TECHNICAL SESSIONS

Technical sessions in the following fields of activity have been tentatively scheduled to include: standards $1^1/_2$, instruments and measurements 1, electrochemistry and electrometallurgy 1, power generation 2, communication 2, electrical machinery 2, basic sciences 1, land transportation 2, power transmission and distribution 2, joint power transmission and protective devices 1, protective devices 2, electronics 1, and industrial power applications 1.

Arrangements also have been made for several technical conferences including: standards, instruments and measurements, electrochemistry and electrometallurgy, communication, basic sciences, electronics, production and application of light, industrial power applications, and air transportation.

CONVENTION COMMITTEE

The personnel of the 1941 winter convention committee, who are making arrangements for the convention to be held in Philadelphia, is as follows: N. E. Funk, chairman; W. B. Morton, vice-chairman; I. M. Stein, treasurer; J. W. Barker, J. V. B. Duer, C. R. Freehafer, L. M. Goldsmith, E. W. Loomis, H. Pender, H. S. Phelps, D. C. Prince, F. W. Shackelford, J. B. Harris, Jr., J. H. Tracy, and R. W. Wilbraham. The chairmen of subcommittees are: R. W. Wilbraham, dinner-dance; I. M. Stein, finance; H. S. Phelps, hotel, meetings, signs, and printing; A. G. Kisner, inspection trips and transportation; Mrs. D. C. Prince, women's activities; D. C. Prince, medal presentation; H. C. Albrecht, publicity and sponsor for women's committee; E. P. Yerkes, registration, information, and reception; J. B. Harris, Jr., smoker and special events; C. D. Fawcett, student activities.

Conferences on Load Swings at Summer, Pacific Coast Conventions

One of the technical conferences held at the 1940 summer convention at Swampscott, Mass., June 24–28, 1940, was on the subject of load swings. Another conference on the subject was held during the Pacific Coast convention at Los Angeles, Calif., August 27–30, 1940, the second conference being in part a repetition of the first. Both are covered in the following report, which was prepared by E. C. M. Stahl, member (chairman 1938–40) of the committee on power generation. Reports of the other technical conferences held during the summer convention appeared in the August issue, pages 337–40.

Considerable attention has been focused on the subject of load swings, turbine-generator governing, and stability, not only when a system is operated alone, but also when it is interconnected with other systems. Because of the widespread interest in this subject and the need of extensive investigation for the ultimate solution of the many problems involved, it was deemed desirable to schedule a conference at which informal discussion would be possible in advance of the preparation and presentation of formal papers before the Institute. The objective of the conference held at Swampscott, Mass., June 25, 1940, was the crystallization of the

problem with particular reference to the functional requirements and limitations of a prime-mover speed governor.

J. B. McClure of the General Electric Company outlined the requirements of governing mechanisms with respect to their being essential, necessary, and desirable. The functions discussed included dead band, uniform incremental regulation, adjustable regulation, similarity in rate of response, accuracy of response for supplemental adjustment, and indications of all adjustments.

A. C. Monteith of the Westinghouse Electric and Manufacturing Company discussed the problem of power-system governing from the viewpoint of the operating engineer as gathered from the answers to a questionnaire to which 20 representative operating companies responded. The general conclusions seem to indicate that there are no outstanding deficiencies in modern governing systems. It seems likely that full advantage is not being utilized of the inherent capabilities of many existing governors. A test program is required to disclose maintenance defects, wrong adjustments, and improper operation. The limitations of the speed governor for interconnected operation must be recognized, and means provided to supplement the governor when close control of frequency or tie-line load is required.

A. P. Hayward of the Duquesne Light Company discussed the simple speed governor with respect to its limitations, requirement of auxiliary equipment to assist it in controlling load, and operating difficulties. From the standpoint of application, the factors needing additional consideration are:

1. Means of adjusting the speed regulation both for steady-state and transient conditions to permit co-ordination of the newer governors with the older governors.

2. Further reduction in the incremental regulation from minimum to maximum load and the elimination of dead spots.

3. Improvements in the speed-changer mechanism to provide the required sensitivity and uniform response.

4. Provision for decreasing the sensitivity of the governor within the continuous maneuvering range.

J. E. McCormack of the Consolidated Edison Company, Inc., of New York discussed the results of a series of tests made to determine the magnitude and period of load swings on the system with a view toward establishing the initiating cause or causes and the effect that the various system-regulating devices had in correcting or amplifying these swings. The general conclusion from these tests is that swings of reasonably large magnitude are caused by manual regulating operations in transferring load from one part of the system to another, or by incorrect anticipation of load changes, rather than by any factor inherent in the system load or regulation equipment. In order to minimize these, frequency indicators with a common reference are being installed in the major stations, so that the turbine throttles will be operated to increase or decrease load in such a way that load will be picked up by a station only on decreasing frequency and dropped off only on rising frequency.

An instrument for recording governor characteristics was described by F. Oppenheimer of the Pennsylvania Water and Power Company. The instrument simultaneously records, on a chart $3\frac{1}{2}$ inches wide, frequency and gate opening or valve position against time, and gate opening against frequency for the corresponding interval of time, from which the inherent speed droop can be determined as a function of the load on the machine.

Additional discussion centered upon problems encountered by various systems. The need of standardizing terms and tests to determine whether or not governors meet guaranteed performance was emphasized. The conference was fortunate in having the attendance of Professor C. R. Soderberg of Massachusetts Institute of Technology who, as chairman of committee number 20 of The American Society of Mechanical Engineers power test code, described the activities of his committee in preparing a code for speed-sensitive elements. An invitation for the co-operation of the AIEE committee on power generation was accepted.

The conference held at Los Angeles, Calif., August 28, 1940, supplemented the one held at Swampscott. Three prepared reports were presented, two of which also had been presented at Swampscott by Messrs. McClure, Monteith, and Hayward. The third report, presented by T. E. Curtis of the Pacific Gas and Electric Company, described a new electronic control system with which a standard flyball governor may be made sensitive to both frequency and load by means of a balanced solenoid that actuates the pilot valve. The proposed control system has yet to stand the test of operating experience, although the essential operation of the controller has been verified in the laboratory under conditions of an artificial power system.

The general discussion that followed the presentation of the written reports disclosed that the operating problems of the western and Pacific Coast systems are not materially different from those discussed at the Swampscott conference by the representatives of eastern systems. Greater interest was shown, however, in the control of hydro turbines and in the reduction of time lag between pilot-valve action and gate movement.

An attendance of 100 at the Swampscott conference and 42 at the Los Angeles conference indicates the timeliness and importance of, and the interest in the subject. It is believed that the purpose of these conferences has been fulfilled, and the indications are that an interesting program on the subject will be provided for the 1941 winter convention.

Supplement Name Changed; Procedure Explained

In order that its name might indicate more accurately the nature of its content, the name of the Supplement was changed by action of the AIEE publication committee, at its October 2, 1940, meeting, to "Supplement to ELECTRICAL ENGINEERING —Transactions Section." As the new name implies, and as has been announced previously, the Supplement contains material which "supplements" the monthly Transactions sections of ELECTRICAL ENGINEERING, comprising those technical-program papers and discussions published in the current annual bound volume of the TRANSACTIONS, but not included in the 12 monthly sections. Thus, a member may receive *all* technical papers and discussions published by the Institute during the year by adding the Supplement to his 12 monthly issues of ELECTRICAL ENGINEERING.

Continuing on the annual basis originally established in 1938, an annual Supplement for 1940 will be issued during December. Under the provisions of the recently adopted changes in publication policy, however, the Supplement is scheduled to be issued semiannually—June and December—beginning with 1941 (*EE, Aug. '40, p. 331–2*). As announced in the October issue (*p. 413–20*) the 1940 Supplement will contain nearly 600 pages, instead of a normal of about 350 pages. This enlargement will absorb part of the large backlog of material awaiting publication built up by certain requirements of the previous publication policy and will constitute a major step toward the realization of one of the major goals of the new policy—much earlier publication of technical papers and discussions. Likewise, as a further necessary step in the transition from the former to the new publication policies, both of the semiannual Supplements for 1941 will contain an abnormally large number of pages. In spite of the enlarged content, the price of the Supplement will be maintained at 50 cents per copy for both 1940 and 1941 to members in the United States and possessions, instead of $1.00 as indicated in the October issue for the 1940 Supplement. The price to members in Canada and all other countries will be $1.00 per copy to cover extra mailing costs.

The new publication policies also are having a marked effect on the content of the monthly Transactions sections of ELECTRICAL ENGINEERING. To enable the publication date of Transactions material to be advanced as called for in the new policy, and to accomplish the correspondingly increased rate of publishing that material as required to absorb the aforementioned backlog within a nominal period of time *and* without adding heavily to the publication budget requirements, the total number of pages in the Transactions sections of ELECTRICAL ENGINEERING has been reduced by approximately the average number of pages previously devoted to discussions. By immediate adherence to the new policy provision which gives preference to papers of six or less pages for the monthly sections—leaving the longer papers for publication in the annual volume —it is expected that members will continue to receive in ELECTRICAL ENGINEERING during the transition period just about as many technical papers on the average as they have been receiving through that channel during recent years. After the transition has been completed—hopefully by the end of 1941—

Future AIEE Meetings

Winter Convention
Philadelphia, Pa., January 27–31, 1941

Great Lakes District Meeting
Fort Wayne, Ind., April 1941

North Eastern District Meeting
Rochester, N. Y., April 30–May 2, 1941

Summer Convention
Toronto, Can., June 16–20, 1941

Pacific Coast Convention
Yellowstone National Park, August 27–29, 1941

members may expect to receive through ELECTRICAL ENGINEERING under the new publication policy a markedly increased number and proportion of technical papers. Readers and authors are warned, however, that, until the necessary transition from the former to the new publication policy is completed, the total number of papers of six or less pages may be too great for all such papers to be included in the temporarily reduced monthly Transactions sections of ELECTRICAL ENGINEERING. In such an event, however, the rule of preference for the shorter papers still will apply.

Additional Committee Personnel

A complete list of the Institute's officers and committees for 1940–41 was published in the September issue, pages 377–81, with the exception of the general committee on transfers, and the technical committees on industrial power applications, electric welding, air transportation, and land transportation. The membership of these committees has now been completed and is listed here.

Transfers

F. O. McMillan, *chairman*, Oregon State College, Corvallis, Ore.

F. M. Craft	G. A. Kositzky
H. C. Don Carlos	E. L. Moreland
Harold Goodwin, Jr.	D. C. Prince

Air Transportation

E. E. Minor, *chairman*, The Glenn L. Martin Company, Baltimore, Md.

H. A. Campbell	V. H. Grant
W. J. Clardy	E. E. Johnson
F. M. Defandorf	J. P. Maxfield
J. H. Gardner	D. C. Prince

Mrs. M. M. Rockwell

Electric Welding

J. D. Wright, *chairman*, General Electric Company, Schenectady, N. Y.

J. H. Blankenbuehler	W. F. Hess
L. W. Clark	S. M. Humphrey
W. B. Crawford	J. H. Lampe
J. W. Dawson	G. G. Landis
Wray Dudley	C. I. MacGuffie
D. D. Ewing	F. W. Maxstadt
O. W. Garman	C. L. Pfeiffer
K. L. Hansen	C. A. Powel
C. E. Heitman, Jr.	E. H. Vedder

Industrial Power Applications

J. J. Orr, *chairman*, United States Rubber Company, 1230 Sixth Ave., New York, N. Y.

E. A. Armstrong	F. C. Nicholson
T. F. Barton	W. A. Perry
E. T. Carlson	D. E. Renshaw
R. F. Chamberlain	H. W. Rogers
C. W. Drake	F. O. Schnure
J. H. Edwards	H. L. Smith
E. Gordon Fox	Herbert Speight
John Grotzinger	L. A. Umansky
F. E. Harrell	E. V. Valk
A. E. Knowlton	R. L. Walsh
E. D. Lilja	B. M. Werly
M. J. McHenry	J. D. Wright

R. H. Wright

Land Transportation

E. B. Fitzgerald, *chairman*, The American Car and Foundry Company, Berwick, Pa.

R. Beeuwkes	W. S. H. Hamilton
L. W. Birch	P. H. Hatch
G. E. Bishop	G. L. Hoard
W. A. Brecht	Fraser Jeffrey
J. C. Davidson	L. C. Josephs
C. M. Davis	F. C. Lindvall
E. G. Davis	P. A. McGee
J. V. B. Duer	R. J. Needham
D. D. Ewing	R. J. Parsons
J. E. Gardner	W. I. Slichter
Selby Haar	Dwight L. Smith
J. S. Hagan	L. J. Turley

W. M. Vandersluis

Nomination of AIEE Officers for 1941 Election

For the nomination of national officers to be voted upon in the spring of 1941, the AIEE national nominating committee will meet during the winter convention, January 27–31, 1941. The officers to be elected are: a president, a national treasurer, three directors, and five vice-presidents, one from each of the even-numbered geographical Districts. Fellows only are eligible for the office of president, and Members and Fellows for the offices of vice-president, director, and national treasurer.

To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1940.

In accordance with the provisions in the constitution and bylaws, as amended during 1935 and quoted in the following paragraphs, actions relative to the organization of the national nominating committee are now under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical district, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical districts; all to be selected when and as provided in the bylaws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical district shall act as a nominating committee of the candidate for election as vice-president of that district, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before January 31 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical districts, if received by the national nominating committee when and as provided in the bylaws; otherwise the national nominating committee shall nominate one or more candidates for vice-president(s) from the district(s) concerned.

Bylaws

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district that by December 15 of that year the executive committee of each district must select a member of that district to serve as a member of the national nominating committee and shall, by December 15, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that district, made by the district executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the national nominating committee shall be published in the March issue of ELECTRICAL ENGINEERING (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in Section 31 of the constitution and Section 23 of the bylaws, which are quoted herewith:

Constitution

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice-presidents shall be signed only by members within the district concerned.

Bylaws

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 (constitution) must be received by the secretary of the national nominating committee not later than March 25th of each year, to be placed before that committee for

New Members

Mr. Institute Member:

A continuous inward flow of new members is as essential to the Institute as are new cells to the body, and they serve the same purpose, namely, to replace natural losses and provide for growth.

The volunteer workers of Section membership committees will do all they can to locate and interview eligible prospects, but their numbers are few and their scope of contact limited. Success will attend their efforts only if they receive the co-operation and assistance of all members.

Send them the names of any eligible prospects that you know of, or, better still, try to interest the prospects yourself as it may be more difficult for the committee members to reach them.

O. C. Brill

Chairman, National Membership Committee

the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with Article VI of the constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) H. H. HENLINE,
National Secretary

November 1, 1940

Personal • • •

ALEXANDER MAXWELL

J. R. NORTH

C. M. GILT

Alexander Maxwell (F'37) director of engineering, Edison Electric Institute, New York, N. Y., has been appointed chairman of the newly created AIEE committee on domestic and commercial applications for 1940–41. He was born at New York, N. Y., May 13, 1878, and educated there. In 1894 he became an assistant in the laboratory and testing departments of the Westinghouse Electric and Manufacturing Company at Newark, N. J., and the following year entered the employ of the Manhattan Electric Light Company, New York, N. Y., as assistant to the electrical engineer. He continued in that position with the New York Edison Company after 1899. From 1912 to 1917 he was director of the general laboratory of the New York Edison Company. During the next two years he was in active service with the United States Army, attaining the rank of major, and later becoming a lieutenant-colonel in the Reserve Corps. He returned to the New York Edison Company in 1919 as engineer on stray current electrolysis and inductive co-ordination of power and communication circuits, and from 1921 to 1923 was engineer of distribution, redesigning d-c distribution system. He became an engineer with the National Electric Light Association, New York, in 1923, on inductive co-ordination, power and communication circuits, and later on research and administrative work. Except for a half year at the United States Army Command and General Staff School in 1925, he continued with NELA until the organization was dissolved and succeeded by the Edison Electric Institute. He was made director of engineering of the latter on its formation in 1933 and has continued in that position since. He is also a member of the AIEE board of examiners.

F. B. Jewett (A'03, F'12) vice-president, American Telephone and Telegraph Company, New York, N. Y., has resigned as president of Bell Telephone Laboratories and becomes chairman of the board of directors. The change will increase the time he has available in an advisory capacity to the Government as president of the National Academy of Sciences and as a member of the National Defense Research Committee. He was born at Pasadena, Calif., September 5, 1879, and received the degree of bachelor of arts from Throop Technological Institute (now California Institute of Technology) in 1898, and that of doctor of philosophy from the University of Chicago in 1902. He was an assistant in physics at the University of Chicago, Chicago, Ill., 1901–02, and in physics and electrical engineering at Massachusetts Institute of Technology, Cambridge, 1902–04. He went with the American Telephone and Telegraph Company in 1904 as a transmission engineer. In 1912 he became assistant chief engineer of the Western Electric Company, in 1916 chief engineer, and in 1922 vice-president. He was made vice-president in charge of research and development of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories in 1925. Doctor Jewett is a past president of the AIEE and has been active in its work and that of other societies. He has received the Edison Medal of the AIEE, the Faraday Medal of the Institution of Electrical Engineers of Great Britain, the Washington Award, and the John Fritz Medal, among other honors. During the World War he served as lieutenant-colonel in the Signal Corps and was awarded the Distinguished Service Medal.

O. E. Buckley (M'19, F'29) has been appointed president of the Bell Telephone Laboratories, New York, N. Y. He has been executive vice-president since 1936, and has been associated with the Bell System since 1914. A biographical sketch of Doctor Buckley appeared in the December 1939 issue, page 537.

J. R. North (A'21, M'29) assistant electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich., has been appointed chairman of the AIEE committee on protective devices for the year 1940–41. He has been a member of the committee since 1934 and was vice-chairman 1938–40. He is also a member of the committees on electrical machinery and on the economic status of the engineer, and of co-ordinating committees 3 and 4 of the standards committee. He was born February 20, 1900, at Cambridge, Mass., and received the degree of bachelor of science in electrical engineering at California Institute of Technology in 1923. He was a substation operator for the Southern California Edison Company, Los Angeles, Calif., 1920–23, and in 1922–23 was an assistant instructor in electrical engineering, California Institute of Technology, Pasadena. He then spent a year as student engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh and Sharon, Pa. Since 1924 he has been associated with Commonwealth and Southern Corporation and its predecessor company, Commonwealth Power Corporation of Michigan, first as engineer in investigation division, then as assistant investigation engineer (1927), and general technical engineer (1931). He has held his present position since 1939. He has also been active in committee work for the American Standards Association, Edison Electric Institute, and Society of Automotive Engineers.

C. M. Gilt (A'21, F'35) inside plant engineer, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the AIEE committee on electrical machinery for the year 1940–41. He has been a member of the committee since 1937, and was also a member 1926–31. He formerly was a member of the standards committee, and is at present a member of its co-ordinating committee 4. Born in Auburn, N. Y., in 1892, he received the degrees of bachelor of arts, University of Rochester, 1914; bachelor of science, Massachusetts Institute of Technology, 1917; and master of science in electrical engineering, Union College, 1919. He entered the test course of the General Electric Company, Schenectady, N. Y., in 1917, and the following year was transferred to the lighting engineering department, continuing there until 1923 when he went to the Brooklyn (N. Y.) Edison Company. He became inside plant engineer in 1926, outside plant engineer in 1931, and assistant electrical engineer in 1932. When the engineering work of the Consolidated Edison system was centralized in 1937 he became inside plant engineer of the Consolidated Edison Company. He is a member of Phi Beta Kappa.

C. C. Levy (A'33) industry engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the Institute's committee on electrochemistry and electrometallurgy for 1940–41. He has been a member of the committee since 1934. He was born September 18, 1886, at Lucea, Jamaica, British West Indies, and studied electrical engineering 1909–12 at the School of Practical Science, Toronto University. During 1905–06 he was a switchboard operator for the New York (N. Y.) Edison Company. He was an electrical draftsman for Canadian General Electric Company, Toronto, 1912–13, and since 1913 has been associated with the Westinghouse company. He was first employed as switchboard

draftsman, became designing engineer in the switchboard department in 1916, and in 1920 was placed in charge of switchboard drafting. He became automatic switching engineer in 1922. Since 1930 he has been engaged in application engineering, specializing in the electrochemical and chemical industries, and recently has been concerned with industry problems and application practice in inductive heating and melting.

J. J. ORR

C. C. LEVY

E. B. FITZGERALD

J. J. Orr (A'30) engineer, central staff, United States Rubber Company, New York, N. Y., has been appointed chairman of the AIEE committee on industrial power applications for 1940–41. He has been a member of the committee since 1937 and is also a member of co-ordinating committee 4 of the standards committee. Born April 9, 1902, at Manistique, Mich., he studied engineering at the University of Michigan. He was employed by the Oakland Motor Car Company, Pontiac, Mich., as an electrician in 1919–20 and as a draftsman 1924–26. When the company became the Pontiac division of General Motors Corporation in 1926 he became an assistant electrical engineer, and in 1928 he became electrical engineer. During 1930–31 he was plant engineer for A. J. Brandt, Inc., construction engineering firm in Detroit, Mich. He joined the staff of United States Rubber Company, New York, in 1932, as electrical engineer. In 1933 he was transferred to Providence, R. I., as plant engineer, and in 1936 was made manager of planning and engineering at Providence. Since 1938 he has been with the central engineering staff, which supervises engineering and development in about 20 plants in the United States and Canada.

E. B. Fitzgerald (A'26, M'31) electrical engineer, American Car and Foundry Company, Berwick, Pa., has been appointed chairman of the AIEE committee on land transportation (formerly the committee on transportation) for the year 1940–41. He has been a member of the predecessor committee since 1935. He was born at Greenfield, Mass., May 20, 1901, and received the degree of bachelor of science in electrical engineering from Norwich University in 1924. In 1924 he entered the graduate student course of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., where he was engaged in special work in connection with the electrification of the Norfolk and Western and Virginian railroads; later he was transferred to Bridgeport, Conn., as service engineer. He entered the employ of the J. G. Brill Company, Philadelphia, Pa., in 1926 as assistant electrical engineer in the automatic car division, and in 1930 was made electrical engineer. He has been with the American Car and Foundry Company since 1935. He has been active also in committee work for the American Transit Engineering Association and the National Fire Protection Association.

W. L. Cisler (M'35) assistant chief engineer, electrical engineering department, Public Service Electric and Gas Company, Newark, N. J., has been appointed chairman of the AIEE committee on power generation for 1940–41. He has been a member of the committee since 1935. Born October 8, 1897, at Marietta, Ohio, he received the degree of mechanical engineer from Cornell University in 1922, and since that time has been continuously employed by Public Service Electric and Gas Company. He entered the service of the company as cadet engineer in the training course, and from 1924 to 1926 was test engineer in the Marion and Kearny generating stations. In 1926 he became assistant chief engineer at the Peterson generating station, and in 1927 chief engineer of the Marion station. From 1931 to 1935 he was planning and installation engineer, and in 1935 he became general superintendent of generation. He was made assistant general manager of the electric department in 1936 and assumed his present position in 1938.

A. E. Anderson (A'23, M'34) switchgear engineering division, General Electric Company, Philadelphia, Pa., has been appointed chairman of the AIEE committee on automatic stations for the year 1940–41. He has been a member of the committee since 1931. Born May 26, 1897, at Falmouth, Mass., he received the degree of bachelor of science in electrical engineering from Worcester Polytechnic Institute in 1920. His affiliation with General Electric began in 1918, in the testing department at Schenectady, N. Y., and was twice interrupted, by service in the United States Army and the Ordnance Department, and by his final year at college. Since 1920 he has been continuously with the company; from 1920 to 1932 responsible for application and design of automatic switching equipment for use with nonrotating apparatus, and since 1932 concerned with both manual and automatic control switchgear. He is the author of papers and articles on switchgear, and holds 60 patents, mostly relating to switchgear and control apparatus.

J. D. Wright (A'36) assistant manager, industrial department, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on electric welding for the year 1940–41. He was born at Baraboo, Wis., April 11, 1887, and received the degree of bachelor of science from the University of Wisconsin in 1909. Since graduation he has been continuously employed by General Electric. He was first a student engineer in the testing department, then engineer in the industrial control engineering department. He was transferred to the steel mill section of the industrial engineering department in 1915 and placed in charge of the section in 1922. In 1930 he became assistant engineer of the industrial department, and in 1936 assistant manager. He was a member of the Institute's former committees on the iron and steel industry and applications to iron and steel products, and is a member of the committee on industrial power applications (chairman 1938–40).

K. S. Wyatt (A'32, M'39) formerly technical director of the Enfield Cable Works, Ltd., London, has joined the staff of the Habirshaw Cable and Wire Division of the Phelps Dodge Copper Products Corporation of New York, N. Y. Mr. Wyatt attended Mount Allison University, Sackville, N. B., Canada, receiving the degrees of bachelor of arts (1921) and bachelor of science (1922), and later did graduate work at Harvard University and the University of Toronto. He was an assistant research chemist for the Carborundum Company, Niagara Falls, N. Y., in 1922–23. The Detroit Edison Company, Detroit, Mich., employed him in 1928 as research engineer on cable insulation. He continued in that position until 1938 at which time he became affiliated with the Enfield Cable Works. Mr. Wyatt is a member of the American Chemical Society and has been associated with a number of national committees on cables and insulation. He is author and co-author of many papers on cable insulation.

C. M. Sherer (A'39) test engineer, Pennsylvania Water and Power Company, Holtwood, Pa., has been awarded the District 2 prize for initial paper for 1939, jointly with K. J. Granbois, for their paper "An Unusual Case of A-C Electrolysis on Single-Phase Power Cables." A native (1895) of Mannheim, Pa., Mr. Sherer received the degree of bachelor of science from Gettysburg College in 1920, and spent a few months with the Edison Lamp Works of General Electric Company at Newark, N. J., before entering the test department of the Pennsylvania Water and Power Company in 1921.

W. R. Schofield (F'32) formerly chief engineer, Leeds and Northrup Company, Philadelphia, Pa., has been made director of engineering. Born October 20, 1895, at Phila-

W. L. CISLER

J. D. WRIGHT

A. E. ANDERSON

delphia, Pa., he studied at the University of Pennsylvania. He has been with Leeds and Northrup since 1916. First employed as a draftsman, he was engaged in designing electrical instruments from 1919 to 1925, and from 1921 was also engineer. He became assistant chief engineer in 1925, and chief engineer in 1928. He is a member of the Institute's committee on electrochemistry and electrometallurgy, and is also a member of The American Society of Mechanical Engineers.

Lloyd Espenschied (A'18, F'30) research consultant, Bell Telephone Laboratories, New York, N. Y., has been awarded the Medal of Honor of the Institute of Radio Engineers, "for his accomplishments as an engineer, as an inventor, as a pioneer in the development of radio telephony, and for his effective contributions to the progress of international radio co-ordination." A native (1889) of St. Louis, Mo., Mr. Espenschied graduated in industrial electrical engineering from Pratt Institute in 1909. After a year as assistant engineer for the Telefunken Wireless Telegraph Company of America, he joined the engineering staff of the American Telephone and Telegraph Company as development engineer in 1910. He was transferred to Bell Telephone Laboratories in 1934. He received the AIEE national prize for best paper in theory and research in 1935.

K. J. Granbois (A'31) test engineer, Safe Harbor Water and Power Company, Conestoga, Pa., has been awarded District 2 prize for initial paper for 1939 jointly with C. M. Sherer, for their paper "An Unusual Case of A-C Electrolysis on Single-Phase Power Cables". Mr. Granbois, a native (1905) of Rosholt, S. Dak., received the degree of bachelor of science in electrical engineering from the University of Minnesota in 1929, and after a year on transformer testing with the Westinghouse Electric and Manufacturing Company at Sharon, Pa., entered the testing department of the Pennsylvania Water and Power Company, Holtwood. He assumed his present position in 1935.

F. A. Compton, Jr. (A'39) d-c armored motor engineering department, General Electric Company, Erie, Pa., was awarded the District 2 prize for best paper for 1939, for his paper "Application of Class B Insulation to Auxiliary Type D-C Motors in Heavy-Duty Service." Mr. Compton, who received the degrees of bachelor of arts in 1927 and electrical engineer in 1928 from Stanford University, has been associated with General Electric Company at Erie since 1929. He was first employed in the motor division of the transportation engineering department and in 1936 was transferred to his present work on d-c armored motors.

E. F. King (A'37) engineer, radiant heat division, C. M. Hall Lamp Company, Detroit, Mich., was awarded the District 2 prize for graduate student paper for 1939 for his paper "Photoelectric Stress Studies of Small Objects in Motion." A native (1913) of Falmouth, Ky., he received the degree of electrical engineer from the University of Cincinnati in 1936. He was employed as electrician by the Pure Oil Company, Cincinnati, Ohio, 1936–37, and was teaching fellow in electrical engineering at the University of Cincinnati for two years before assuming his present position.

H. C. Robertson (A'40) Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., received the District 2 prize for Branch paper for 1939, for his paper "Electricity in Medicine", written while he was a student at Johns Hopkins University. He received the degree of bachelor of engineering from that institution in 1939, and after a summer's work for the Eastern Shore Public Service Company, Salisbury, Md., entered the student course at Westinghouse in the fall of that year.

R. E. Bailey (A'37) formerly division manager, Utah Power and Light Company, Park City, Utah, has been appointed manager of the southern division of the company. He joined the company in 1914 as power salesman, becoming superintendent of power sales in 1915, assistant to the commercial manager in 1924, and manager of the Park City division in 1926.

W. D. Coolidge (A'10, M'34) director of research laboratory, General Electric Company, Schenectady, N. Y., has been appointed to the recently organized National Inventor's Council, created to encourage civilian inventions as part of the national defense program.

Obituary • • •

Charles Frederick Uebelacker (A'90, M'93) retired vice-chairman, Ford, Bacon and Davis, Inc., New York, N. Y., died September 17, 1940. He was born at Rochester, N. Y., April 8, 1868, and completed the electrical-engineering course at Princeton University in 1890. He entered the employ of the Brush Electric Manufacturing Company, Cleveland, Ohio, as an apprentice and within three years rose to the position of assistant superintendent. In 1893 he became associated with the Consolidated Traction Company, N. J., becoming successively division superintendent, master mechanic, and chief engineer. From 1897 to 1899 he was general manager of works of the Peckham Motor Truck and Wheel Company, Kingston, N. Y. In the latter year he went with the firm of Ford, Bacon and Davis and remained with this organization until his retirement in 1936. For this firm he served first as vice-president and general manager of the Elmira (N. Y.) Water, Light and Railroad Company; in 1901 assumed the duties of chief engineer of Ford, Bacon and Davis in New York, and in 1912 was made a partner in the firm. When the firm was incorporated in 1921 he became chairman of the board of directors, serving as such until 1927. In 1934 he was made vice-chairman until his retirement. During the World War he acted as consulting engineer and chief technical adviser to D. C. Jackling, director of explosives for the War Department. Mr. Uebelacker was a member of The American Society of Mechanical Engineers; Princeton Alumni Association of Northern New Jersey; Princeton Engineering Association; and, prior to his retirement, the Engineers Club, New York, and various other clubs.

William Charles Boyrer (A'09, M'22, F'24) retired electrical engineer of the Consolidated Edison Company of New York, Inc., died September 28, 1940. He was born in New York, N. Y., December 18, 1869; he received the degrees of bachelor of science in 1890 from the College of the City of New York, and mechanical engineer in 1891 and master of mechanical engineering in 1892 from Cornell University. In 1892 he entered the student course of the General Electric Company; from November 1892 to June 1893 was affiliated with Queen and Company, Philadelphia, Pa.; and from 1893 to 1894 with Pepper and Register, Philadelphia. He was associated with the New York Navy Yard from 1894 to 1895; the New York and New Jersey Telephone Company, 1895–1903 (division engineer 1899–1903); assistant to superintendent of construction, American Telephone and Telegraph Company, 1903–08; electrical engineer, Public Service Commission for the First District, State of New York, 1908–24; executive staff, New York Edison Company, 1924. He remained with this company and its successor, the Consolidated Edison Company, until his retirement in 1937. Mr. Boyrer was the author of several books on telephone engineering. He was a member of the National Electric Light Association; Telephone Pioneers of America; Theta Delta Chi; the Steuben Society of America, the Brooklyn Engineers' Club, and the

Mathematical Society of America. He was active in the forming of the AIEE South Carolina Section.

Charles Ambrose Crapo (M'23) equipment and buildings engineer, Mountain States Telephone and Telegraph Company, Denver, Colo., died September 2, 1940. He was born November 4, 1876, at Chicago, Ill., and educated there. He was employed as a switchboard installer by the Chicago Telephone Company in 1890; became instrument installer in 1893, and switchboard maintenance man in 1896. In 1902 he was transferred to the Colorado Telephone Company, Denver, and in 1905 was appointed equipment engineer. When the Colorado Telephone Company and the Rocky Mountain Bell Telephone Company consolidated in 1911 to form the Mountain States Telephone and Telegraph Company, he continued in the same position, and in 1920 became engineer of equipment and buildings. He had completed 50 years of telephone service on June 1, 1940.

William G. Quirk (A'16, M'27) engineer, division of street lighting and exterior electrical distribution, Department of Water Supply, Gas, and Electricity, City of New York, N. Y., died September 10, 1940. He was born in New York, N. Y., February 28, 1879, and studied at Cooper Union. Since 1900 he had been associated with lighting for the City of New York. He was inspector of construction and operation of electric building and street lighting installations, later becoming general inspector in charge of the bureau of lamps and lighting. In 1915 he was made supervising general inspector in charge of the division of street lighting and exterior electrical distribution, and continued to hold that position until his death. He was also a member of the Illuminating Engineering Society.

Savel Bernard Kyne (formerly Kanevsky) (A'37) assistant electrical engineer, Connecticut Light and Power Company, Willimantic, Conn., died August 21, 1940. Born in Russia, July 30, 1885, he received the degree of bachelor of science in electrical engineering from Cooper Union in 1919. He joined the Connecticut Light and Power Company in 1924 as assistant electrical engineer on design of substations and transmission lines, at Norwich, Conn., and was later transferred to Willimantic.

Kenneth John Kiefer (A'36) transit man, Works Progress Administration, Cleveland, Ohio, died March 9, 1940, according to information recently received. He was born at Cleveland March 17, 1911, and received the degree of bachelor of science in electrical engineering from the Case School of Applied Science.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on October 17, 1940, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Evans, R. D., consulting transmission engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Harrell, F. E., assistant chief engineer, Reliance Electric and Engineering Co., Cleveland, Ohio.

Martindale, Roy, assistant chief electrical engineer and general manager, Bureau of Power and Light, Los Angeles, Calif.

Nye, H. V., engineer in charge, switchgear design, Allis-Chalmers Manufacturing Company, West Allis, Wis.

4 to Grade of Fellow

To Grade of Member

Blankenbuehler, J. H., design engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Bowman, J. H., associate professor of electrical engineering, Purdue University, West Lafayette, Ind.

Daley, J. L., assistant professor of electrical engineering, Yale University, New Haven, Conn.

Dunn, Charles, associate electrical engineer, The Bonneville Power Administration, Portland, Ore.

Evans, C. W., editor, *Electrical South*, Atlanta, Ga.

Garrett, W. A., district plant engineer, American Telephone and Telegraph Company, Albuquerque, N. Mex.

Hills, H. W., engineer, Jackson and Moreland, Boston, Mass.

Lee, A. W., vice-president in charge of operation, Louisville Gas and Electric Company, Louisville, Ky.

Meyer, E. M., chief electrical engineer, Victor Insulators, Inc., Victor, N. Y.

Paxson, H. R., relay engineer, Philadelphia Electric Company, Philadelphia, Pa.

Ramakrishna, R., superintendent of transmission lines, Government of Mysore, Bangalore, S. India.

Sawford, Frank, mechanical and electrical engineer, Vancouver, B. C., Canada.

Steeves, C. M., electrical engineer, Sao Paulo Tramway Light and Power Co., Sao Paulo, Brazil.

Tole, J. H., sales engineer, Westinghouse Electric and Manufacturing Company, Memphis, Tenn.

Zimmerman, S. W., research engineer, General Electric Company, Pittsfield, Mass.

15 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before November 30, 1940, or January 31, 1941, if the applicant resides outside of the United States or Canada.

United States

1. North Eastern

Cady, C. A. (Member), General Radio Company, Cambridge, Mass.

Tener, R. S. (Member), General Electric Company, Lynn, Mass.

2. Middle Eastern

Anderson, A. A., Pennsylvania Power and Light Company, Sunbury, Pa.

Brangan, C. S., Bra Bon Electric Company, Incorporated, Philadelphia, Pa.

Brown, A. G., Chicago Pneumatic Tool Company, Cleveland, Ohio.

Creveling, A. B., Jr., American Car and Foundry Company, Berwick, Pa.

Cullen, R. F., Philadelphia Electric Company, Philadelphia, Pa.

Dyke, L. B., Philadelphia Electric Company, Philadelphia, Pa.

Gargan, T. V., Anaconda Wire and Cable Company, Philadelphia, Pa.

Howe, E. G., General Electric Company, Philadelphia, Pa.

Jungk, H. G. (Member), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

McKean, A. H. (Member), Allegheny Industrial Electrical Company, Incorporated, Pittsburgh, Pa.

Phair, R. S., E. G. Budd Manufacturing Company, Philadelphia, Pa.

Rupar, A. B., Elkland Electrical Company, Incorporated, Elkland, Pennsylvania.

Schreiber, M. A., Bethlehem Steel Company, Sparrows Point, Md.

Senior, G. A., Philadelphia Electric Company, Philadelphia, Pa.

Steinbright, W. G., Philadelphia Electric Company, Philadelphia, Pa.

Theon, A. B., Reliance Electric and Engineering Company, Cleveland, Ohio.

Tibbs, R. H. (Member), Chesapeake and Potomac Telephone Company, Washington, D. C.

Warren, S. R., Jr. (Member), Moore School of Electrical Engineering, Philadelphia, Pa.

Weeks, L. H., Copper Wire Engineering Association, Washington, D. C.

3. New York City

Cornell, B. S., New York Telephone Company, New York, N. Y.

Ingram, M., Brooklyn Edison Company, Incorporated, Brooklyn, N. Y.

MacDaniels, R. B., New York City Tunnel Authority, New York, N. Y.

McManus, J. J., Consolidated Edison Company of New York, Incorporated, New York, N. Y.

Nelson, J. K., Western Union Telegraph Company, New York, New York.

Overgaard, H., Ebasco Services Incorporated, New York, N. Y.

Reinhardt, E. F., Public Service Electric and Gas Company, Jersey City, N. J.

Walker, R. I., New York City Board of Transportation, IRT Division, New York, N. Y.

4. Southern

Morton, H. C., Westinghouse Electric and Manufacturing Company, Memphis, Tenn.

Welch, W. T., New Orleans Public Service Incorporated, New Orleans, La.

5. Great Lakes

Ambelang, C. E. (Member), Public Service Company of Northern Illinois, Chicago, Ill.

Bowman, R. J., Illinois Testing Laboratories, Incorporated, Chicago, Ill.

Briggs, W. A., Carnegie-Illinois Steel Company, Chicago, Ill.

Gray, P. G., Michigan State College, East Lansing.

Kennedy, J. T. (Member), Cutler-Hammer, Incorporated, Milwaukee, Wis.

Kezer, J., Commonwealth Edison Company, Chicago, Ill.

Lenten, N. W., Cutler-Hammer, Incorporated, Milwaukee, Wis.

Neal, E. C., Ford Motor Company, Dearborn, Mich.

Nicolai, N. A. (Member), Indiana Bell Telephone Company, Indianapolis, Indiana.

Posselt, E. J. (Member), Cutler-Hammer, Incorporated, Milwaukee, Wis.

Raven, G. F., The Commonwealth and Southern Corporation, Jackson, Mich.

Steel, F. K. (Member), Chicago, Burlington and Quincy Railroad Company, Chicago, Ill.

7. South West

Duerkob, M. F., Bussmann Manufacturing Company, St. Louis, Mo.

Greenslade, W. F., Jr., J. W. Beretta Engineers, Incorporated, San Antonio, Texas.

Norvell, R., West Texas Utilities Company, Dalhart, Texas.

Salis, A. E., Agricultural and Mechanical College of Texas, College Station, Texas.

Williams, J. H., Carter Oil Company, Tulsa, Okla.

8. Pacific

Brokaw, G. K., care C. B. Bentley, 216 Pine St., San Francisco, California.

Bruce, W. C., Southern California Telephone Company, Los Angeles, Calif.

Gansle, K. A., Southern California Telephone Company, Los Angeles, California.

Gould, E. H., Jr., Navy Yard, Mare Island, Calif.

Harsin, A. W., Southern California Telephone Company, Los Angeles, Calif.

Nott, W. M., Sangamo Electric Company, San Francisco, Calif.

Pickering, W. H., California Institute of Technology, Pasadena, Calif.

Poynter, W. F., Pacific Electric Manufacturing Corporation, San Francisco, Calif.

Reibold, C. T., Southern California Telephone Company, Los Angeles, Calif.

9. North West

Burton, F. J., Seattle Transit System, Seattle, Wash.

Green, J. P., Washington Water Power Company, Spokane, Wash.

Hatfield, D. W., Utah Copper Company, Garfield, Utah.

Ryan, J. C., Montana Power Company, Butte, Montana.

Uhlig, R. A., Washington Water Power Company, Spokane, Wash.

10. Canada

Brown, R. J. (Member), University of Toronto, Toronto, Ont.

Cadario, H. P., Hydro Electric Power Commission of Ontario, Toronto, Ont.

Clement, L. D. L., Hydro Electric Power Commission of Ontario, Toronto, Ont.

Phillips, N. B., Hydro Electric Power Commission, Toronto, Ont.

Smith, W. H., English Electric Company of Canada, Limited, St. Catharines, Ont.

Total, United States and Canada, 67

Elsewhere

Chemor, T. A. (Member), Mexico Tramways Company, Mexico, D. F., Mexico.

Fuller, R. G. (Member), British-American Tobacco Company, Limited, Shanghai, China.

Hogle, C. R. (Member), The Panama Canal, Balboa Heights, Canal Zone.

Rodriguez, E., Manila Steamship Company, Manila, P. I.

Wilson, R. S., Manila Electric Company, Manila, P. I.

Total, elsewhere, 5

Of Current Interest

From AEC . . .

ITEMS appearing under this heading are from the news service of American Engineering Council.

Army-Navy Defense Orders Mount as Congress Completes Appropriations

Organization of an Atlantic Fleet by the Navy, a $25,000,000 loan to China to be repaid by shipments of tungsten, the extension of embargoes on United States exports of war materials and supplies, and the completion of an appropriation program by Congress allotting over $12,000,000,000 for defense needs marked an eventful month in Washington.

Of the money earmarked for defense, $8,347,400,507 is in direct appropriations, while an additional sum approaching $4,000,000,000 takes the form of contract authorizations to be met from later appropriations. Not included is full cost of the two-ocean navy, which will cost an estimated $5,000,000,000 over a five-year period, and for which direct appropriations of only $148,000,000 so far have been made.

Major items to be secured by this expenditure include:

Complete equipment for an army totaling 1,400,000 men, and arms for an additional 600,000.

Air forces of 25,000 planes for the Army and 10,000 for the Navy.

Construction and rehabilitation of a large number of Army and Navy bases.

Financing of munitions plants.

Two new units have been created by executive order to handle specific problems connected with the defense drive. The Defense Communications Board will coordinate plans for the war-time use of cable, wire, and radio facilities with due regard to the needs of the armed services, the Government, and the general public. It is composed of the chairman of the Federal Communications Commission, the director of naval communications, the chief signal officer of the Army, an assistant secretary of state, and an assistant secretary of the treasury. The Health and Medical Advisory Committee will advise on the problem of securing adequate medical staffs for the expanded Army and Navy without unnecessary dislocation of present medical facilities in both rural and urban districts.

The United States has now adopted the policy of placing an embargo upon the exportation of scrap steel, an important war material, to all countries except Great Britain and the countries of the Western Hemisphere. Also subject to strict export licensing are aircraft, airplane engines, aviation gasoline, and tetraethyl lead, as well as equipment for their production and technical information useful in the design, construction, and operation of such equipment.

An announcement of general policy by the National Defense Advisory Commission early in September calling for full compliance with labor laws by Government contractors has been followed up by an informal opinion on the part of Attorney-General Robert H. Jackson to the effect that firms which have been found to be violators of the National Labor Relations Act may be refused defense contracts until the finding is reversed by a court.

MANY CONTRACTS AWARDED

Actual placing of defense orders is going on at so rapid a rate that attempted summaries are out of date before they can be printed. The Navy signed contracts for 200 new vessels on the day the appropriation act making them legal became law, and the Army has awarded over $1,000,000,000 in orders in one eight-day period. A recent unofficial survey made by Moody's Investors Service estimates unfilled orders in the United States to supply domestic and foreign demands at over $8,000,000,000, with actual awards by the American Army and Navy in the period from July 1 to September 25, 1940, as follows: ships, $4,471,744,000; construction, $474,177,000; automobiles, $316,627,000; aircraft, $737,428,000; arms, $309,230,000; chemicals, $119,217,000; railroad equipment, $97,267,000. Since this date many additional contracts have been awarded, and construction contracts for 50 munitions plants to cost over $500,000,000 were pending at press time.

Machine-tool builders have orders on hand totaling $750,000,000 from both domestic and foreign sources, according to a survey by the magazine *American Machinist*, and is scheduling deliveries well into 1941. The present annual capacity of the industry is set at $450,000,000, which will be increased to $500,000,000 by the end of 1940.

Efforts are being made to decentralize defense orders, and particularly to stimulate the construction of new plants in non-industrial areas remote from frontiers to minimize the interruption to production from possible bombing raids. The War Department is reported to be suggesting the construction of air-raid shelters for the use of workers engaged in the production of munitions.

HOUSING FACILITIES

An allotment of $45,762,500 has been made to the Public Buildings Administration, a division of the Federal Works Agency, for the construction of housing projects to serve the Army. This sum is expected to provide accommodations for at least 13,000 families, to be built under cost-plus-a-limited-fee contracts. The first 70 projects to be designated were located in 28 states, Hawaii, and Puerto Rico. In 19 instances the necessary land already was owned by the Army; in the others it must be acquired. Funds for this work were allotted to the Army by Congress subject to a maximum cost limitation of $3,500 per dwelling unit, including land, utilities, and services, and the program will be supervised by the PBA in conformity with an official request by the Secretary of War.

Employment of Engineers in Defense Program

Engineers who wish to offer their services to the Federal Government in the defense program have three main avenues of approach: (1) direct employment; (2) engagement on a consulting basis; and (3) as an employee or consultant of a contractor having a Government contract. A brief outline of how employment in these three categories may be accomplished follows.

DIRECT EMPLOYMENT

With relatively few exceptions, employment in Government departments, bureaus, independent agencies, and the like is under Civil Service rules and regulations. Competitive examinations produce so-called eligible lists, from which names are certified to those Government agencies making requests. Personnel is being added to several agencies directly concerned with the defense program, such as War, Navy, and the Defense Commission, but most appointments are being made from Civil Service eligible lists already in existence. Many jobs are being handled by calling reserve officers of the Army and Navy to active duty. Thus the chance of obtaining direct employment is somewhat remote for those not having Civil Service status or not being in the organized reserves.

CONSULTING BASIS

The engagement of engineers on a consulting basis is handled by each Government agency in accordance with rules and regulations of long standing, although in a few cases recent simplifications to expedite procedure have been made. In general, compensation is on a per diem basis, and only in exceptional cases does the rate exceed $25 per day. Many Government agencies at times use consultants, but at the present time and in carrying out the defense program, the Army, Navy, and the Panama Canal are the principal agencies taking on engineering consultants.

Applications for consulting work in the Army are being handled by the recently appointed Construction Advisory Board consisting of Francis Blossom, Forrest S. Harvey and J. F. C. Dresser. Communications to this board should be addressed to 1125 Munitions Building, Washington, D. C. Requests for consideration should be accompanied by a full statement of experience, especially records of jobs accomplished. Applications from engineering firms as well as from individuals may be sent to this board. A similar list for the Navy is being compiled by Lieutenant A. D. Hunter, Bureau of Yards and Docks, Navy Department, Washington, D. C.

As is generally known, the national engineering societies have sent questionnaires to their members to compile information respecting those individuals or firms who are available for consulting work. The information gleaned from these questionnaires is now filed with the more important Government agencies. Members of engineering societies should address their communications to the secretaries of their respective societies.

CONTRACTORS' STAFFS

Contractors on defense work of course will engage their own employees and consultants. The policy adopted by the Government is to award contracts, whether for the consulting services of engineers, or for construction, to those qualified to handle the work who reside in the region where it is to be done. In a few cases, the construction contract also includes the design, but this is exceptional. However, engineering firms that are also contractors might well make their qualifications known to the Construction Advisory Board.

It should be understood that the National Defense Advisory Commission itself awards no contracts, but merely serves as a coordinator to assist the regular Federal agencies in carrying out their individual programs.

Other Societies

Industrial Research Institute to Conduct Defense Inventory

Problems of industrial-research management and of the design of research laboratories were discussed by some 50 active executives in this field at the meeting of the Industrial Research Institute held September 27–28, in Swampscott, Mass. The meeting included a session of the organization's executive committee, technical sessions featuring addresses on pertinent subjects and round-table discussions, and inspection trips to nearby industries.

An affiliate of the National Research Council, the Industrial Research Institute was organized several years ago for the purpose of improving efficiency and effectiveness in the management of industrial research, through co-operation of its members. The membership is composed of industrial concerns maintaining research laboratories as a part of their organizations. Top executives in charge of research of the member companies represent them in the activities of the group.

At the business session, which closed the two-day meeting, the members voted to cooperate in a survey of special facilities and key personnel of their respective organizations in the interest of the national-defense program. It was announced also that the office of the secretary was being moved from New York to 8 South Michigan Avenue, Chicago, Ill., to be near that of the chairman, H. Earl Hoover, vice-president, The Hoover Company. Maurice Holland (A'23, M'30) director, division of engineering and industrial research, National Research Council, will continue to represent the organization at its New York office.

New "Who's Who in Engineering"

Engineers throughout the country now are being canvassed for biographical material preparatory to publication of a new (fifth) edition of "Who's Who in Engineering." Like the preceding edition (1937) the new volume is being produced under the editorship of Doctor W. S. Downs and will be published by the Lewis Historical Publishing Company, New York, N. Y.

Qualifications for inclusion in the volume have been established by a committee composed of the following: A. A. Potter, *chairman*, dean, schools of engineering, Purdue University; L. B. Lent, *vice-chairman*, executive secretary, American Engineering Council; F. L. Bishop, secretary, Society for Promotion of Engineering Education; C. E. Davies, secretary, American Society of Mechanical Engineers; H. H. Henline, national secretary, American Institute of Electrical Engineers; T. Keith Legare, secretary, National Council State Boards of Engineering Examiners; A. B. Parsons, secretary, American Institute of Mining and Metallurgical Engineers; G. T. Seabury, secretary, American Society of Civil Engineers; S. L. Tyler, secretary, American Institute of Chemical Engineers; J. A. C. Warner, secretary and general manager, Society of Automotive Engineers.

New ASME Officers. Election of the following officers has been announced by The American Society of Mechanical Engineers to serve the organization during 1941:

President: William A. Hanley, director, Eli Lilly and Company, Indianapolis, Ind.

Vice-Presidents: Samuel B. Earle, research engineer and dean of engineering, Clemson Agricultural and Mechanical College, Clemson, S. C.; Frank H. Prouty, a partner in Prouty Brothers Engineering Company and Industrial Appraisal Company, Denver, Colo.; and Edwin B. Ricketts, mechanical engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.

Managers: Huber O. Croft, professor of mechanical engineering and head of the department, University of Iowa, Iowa City; Paul B. Eaton, consulting engineer, and professor and head of mechanical-engineering department, Lafayette College, Easton, Pa.; and George R. Hulse (M'22) chief engineer, The Safety Car Heating and Lighting Company, New Haven, Conn.

Future Meetings of Other Societies

Acoustical Society of America. Fall meeting, November 14–15, 1940, Chicago, Ill.

American Association for the Advancement of Science. December 27, 1940–January 2, 1941, Philadelphia, Pa.

American Institute of Chemical Engineers. 33d annual meeting, December 2–4, 1940, New Orleans, La.

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 17–20, 1941, New York, N. Y.

American Physical Society. 238th meeting, December 1940, Pasadena, Calif.

239th meeting (annual), December 26–28, 1940, Philadelphia, Pa.

American Society of Civil Engineers. Annual meeting, January 15–18, 1941, New York, N. Y.

American Society of Heating and Ventilating Engineers. 47th annual meeting, January 27–29, 1941, Kansas City, Mo.

American Society of Mechanical Engineers. Annual meeting, December 2–6, 1940, New York, N. Y.

American Society of Refrigerating Engineers. 36th annual meeting, December 2–6, 1940, New York, N. Y.

National Exposition of Power and Mechanical Engineering, 14th. December 2–7, 1940, New York, N. Y.

National Research Council. Highway Research Board, 20th annual meeting, December 4–6, 1940, Washington, D. C.

Society of Naval Architects and Marine Engineers. Annual meeting, November 14–15, 1940, New York, N. Y.

ASME Annual Meeting. The 61st annual meeting of The American Society of Mechanical Engineers will be held in New York, N. Y., December 2–6, 1940, with meeting headquarters at the Hotel Astor instead of at the Engineering Societies Building as in previous recent years. More than 100 technical papers on such specialized subjects as aeronautics, applied mechanics, fuels, hydraulics, metals engineering, machine-shop practice, management, materials handling, petroleum, steam power, railroads, textiles, heat transfer, and process industries will be presented by leading experts in these fields. To accommodate all these papers, 44 sessions are being scheduled, including 6 for Monday evening, December 2.

Chemical Exposition and Conference. An industrial chemical conference will be held in connection with the National Chemical Exposition, at Chicago, Ill., December 11–15, 1940. New developments in chemistry and chemical engineering will be discussed in papers to be presented on December 12 to 14. The conference and exposition are sponsored by the Chicago Section of the American Chemical Society.

1941 Mechanical Catalog. The 30th annual ASME Mechanical Catalog and Directory, 1941 edition, has just come off the presses and is now being distributed to members of The American Society of Mechanical Engineers as part of their membership privileges. Nonmembers of that society may obtain copies from ASME headquarters, 29 West 39th St., New York, N. Y., for $3.00 each.

Library

OPERATED jointly by the AIEE and the other founder societies, the Engineering Societies Library, 29 West 39th Street, New York, N. Y., offers a wide variety of services to members all over the world. Information about these services may be obtained on inquiry to the director.

Periodical Exchange Affected by War

In spite of the war, the Engineering Societies Library is experiencing no difficulty in its receipt of technical periodicals from Great Britain. However, only a few engineering magazines reach the Library now from continental Europe. The 350 or more periodicals from England and other parts of the British Empire are coming through with unusual regularity except in one or two instances since the beginning of the war when the ship carrying a batch of them was sunk by a torpedo or a mine. However, correspondence with the publishers soon brought replacements for all lost copies.

The Allied blockade of Germany failed to stop the flow of German magazines to the Library through Italy. But, with the entrance of the latter country into the war, the Library failed to receive German and Italian publications for several months. Now, some of the German periodicals are being received again through Siberia and Japan, as indicated by the postmarks on the wrappers. *Genie Civil* and other French periodicals ceased arriving at the Library a few weeks after the surrender of France.

To avoid the loss of valuable publications being sent to and received from the British Isles and continental Europe through exchange agreements between engineer-institutions there and the Engineering Societies Library and its co-operating organizations, namely, American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the AIEE, arrangements have been completed to tore them in the country of origin until the end of hostilities. Similar arrangements during the World War proved so satisfactory that only one or two sets of foreign periodicals failed to be completed with the resumption of commerce between belligerents.

Industry • • • •

Defense Inventions to Be Judged by National Inventors Council

Civilian inventions relating to national defense are to be evaluated by a technical staff set up by the National Inventors Council, according to recent report. One division of the staff will be concerned with electrical inventions; other divisions with mechanical and chemical inventions.

The Council expects to establish offices in Washington, D. C., where it will serve as a clearing house for civilian suggestions for improving defense and also as a liaison body to relay assignments from defense officials to the inventors best equipped to solve the problems presented. W. D. Coolidge (A'10, M'34) director of research laboratories, General Electric Company, is the member of the Council especially concerned with electrical problems.

New Laboratory for Best Foods

A new $150,000 research and development laboratory has been built and placed in operation by The Best Foods, Inc., at its Bayonne, N. J. plant. The new building is devoted entirely to laboratories and pilot-plant equipment layouts and includes in addition to the general-control-laboratory space a variety of special-purpose facilities housed largely in individual rooms and laboratories. Among the latter are an experimental bakery, four constant-temperature rooms with temperature-regulating and recording equipment, a special bacteriological laboratory, an optical-instruments room, an organic-research laboratory, and a product-development laboratory. About one-fifth of the laboratory space is available for pilot-plant equipment. In a special photographic dark room is housed a Hilger quartz spectrophotometer, which is said to be one of few in the United States. One of the uses of this instrument is to assist in the check and control of vitamin-*A* content of the company's vegetable margarine product.

Included among the large variety of services are steam, compressed air, a four-wire electrical system, and a special intralaboratory telephone system. Lighting is of the indirect type. As a special safety feature, balconies are provided on both of the two floors above ground, providing an egress from every laboratory in the building.

Expansion Program Announced by General Electric Company

A $50,000,000 expansion program recently was announced by Charles E. Wilson, president of the General Electric Company, "for all kinds of plants, equipment, offices, and warehouses." The expansion will affect mainly the company's seven largest factories at Schenectady, N. Y., Erie, Pa., Lynn, Mass., Pittsfield, Mass., Bridgeport, Conn., Philadelphia, Pa., and Fort Wayne, Ind. A substantial part of the expansion program is for the production of national-defense materials.

While the expansion has not been definitely allotted among the various plants, Mr. Wilson said that the largest single item would be some $8,000,000 for the Erie plant where turbines will be made for the United States Navy. The Schenectady expansion will include facilities for manufacturing radio transmitters and receivers for the Army and Navy Signal Corps. The program is expected to increase the company's employment rolls from its present all-time high of 90,000 to 95,000 or 100,000 during the next 15 months.

Electrical Exposition Postponed

Almost coincidentally with the announcement that an electrical-engineering exposition would be held in Philadelphia, Pa., January 27–31, 1941, world conditions became more unsettled, resulting in apprehension which was reflected in slowing the progress of the exposition. "Because of this development," the exposition management has announced, "it appeared that the size and scope of this exposition would not meet the expectations of its committee and management. Being unwilling to project anything less important and consequently less beneficial to the profession and industry, they both believe it would be inopportune to carry through with the present plans in the limited time remaining. It has therefore been decided to postpone the exposition to another year."

"Bell Laboratories Record" Marks 15th Anniversary

The *Bell Laboratories Record*, in its September 1940 issue, commemorates 15 years of existence, the first issue having appeared in September 1925, eight months after the formation of the Laboratories. Its object has been and is to chronicle the activities of the Laboratories for its own staff and for engineers and scientists in the same or related fields.

Initially distributed to the staff of the Laboratories and that of the department of development and research of the American Telephone and Telegraph Company (now a part of Bell Laboratories), the magazine now has a circulation of more than 11,000, including about 700 paid subscribers, and is distributed to administrative and technical personnel of the Bell System, libraries, educational institutions, and technical writers. P. B. Findley (A'27, M'34) is editor, and G. F. Fowler (A'29) circulation manager.

C. G. Suits Assigned New Duties. Known to AIEE members through authorship of several Institute papers, Doctor C. Guy Suits has been appointed assistant to the director of the General Electric Company's research laboratory at Schenectady, N. Y. The post is a new one and will permit Doctor Suits to continue his research while assuming some administrative duties. A graduate of the University of Wisconsin (1927) where he majored in physics and mathematics, Doctor Suits later studied at the Institute of Technology at Zurich, Switzerland, where he obtained the degree of doctor of science in 1929. He has been associated with the General Electric research laboratory since 1930. In 1937 he was chosen by Eta Kappa Nu, honorary electrical-engineering fraternity, to receive its award as the outstanding young electrical engineer of that year. He has been granted 52 patents.

"Time Capsule" Sealed. Buried in a 50-foot well in front of the Westinghouse exhibit building at the New York World's Fair, the "time capsule", an 800-pound seven-foot "cupaloy" metal cylinder containing records of 20th-century life for the information of scientists in the year 6939, has been on display for two years. On September 23, 1940, the capsule was sealed by a compound of pitch and other chemicals, 500 pounds of which was poured down the shaft of the well. Among the records in the capsule is a copy of the 50th Anniversary (May 1934) issue of ELECTRICAL ENGINEERING (see *EE, Oct. '38, p. 430*).

Television in Army Maneuvers. A mobile television unit was used to send scenes of troop movements to the headquarters of the "defending army" in the recent United States Army maneuvers in upper New York State. The campus of St. Lawrence University, Canton, N. Y., was the base of operations for what is said to be the first experiment in the use of television for military purposes. Television pick-up equipment was sent to the scene of military operations on a truck, followed by an Army truck carrying a motor-generator unit. The mobile unit, powered with a 25-watt relay transmitter, sent images to a relay receiver on the chapel tower of the University, where the images were checked and sent via coaxial cable to the control room in the physics building, where a 50-watt transmitter was installed. There the images were scanned on a monitor and retransmitted to television receivers at army headquarters in Canton,

Heveulton, and De Kalb Junction, N. Y. In addition to transmitting military maneuvers, the equipment was used to transmit programs for the entertainment of the officers.

Westinghouse Doubles Radio-Plant Space. Three new buildings are being constructed by the Westinghouse Electric and Manufacturing Company for its radio division in Baltimore, Md. The first, a temporary timber structure providing 34,000 square feet of manufacturing space has just been completed. Two additional two-story brick-and-steel buildings, which will add approximately 35,000 square feet of manufacturing, laboratory, and office space, are scheduled for completion by November 15.

(A'34), all of the Westinghouse company. D. W. Atwater (A'34) presided. Tours of the lamp manufacturing department, the special-products manufacturing department, and the engineering and research laboratories, and an evening session on bactericidal ultraviolet applications completed the conference.

Among the devices and developments described and demonstrated to the visitors were the Klystron, a new electronic tube for generating ultrahigh-frequency radio waves (tube demonstrated generates 40-centimeter waves and has an output of 150 watts); an ultrahigh-speed X-ray tube capable of making X-ray pictures in one-millionth of a second; new discoveries in bactericidal ultraviolet applications including the instantaneous killing of micro-organisms by intense momentary applications of ultraviolet radiation; and some of the latest developments and devices in fluorescent lighting.

Industrial Scholarships at Cornell. The Cornell University College of Engineering has authorized the use of part of the John McMullen Scholarship Fund to create John McMullen Industrial Scholarships for apprentices in industry selected by the officers of the companies for which they work as men whose value would be increased by an engineering education. Four scholarships of $400 each will be awarded each year. Recipients must be high-school graduates qualified to meet the entrance requirements of the college, must have worked in industry, preferably in a training course, and must be recommended by their employers. It is expected that they will return to the organizations by which they previously were employed. Recipients of the first four scholarships, and nominating companies, are:

S. G. Bohle, Schenectady, N. Y.—General Electric Company; T. J. Hildabrand, Altoona, Pa.—Pennsylvania Railroad; William Evans, Syracuse, N. Y. —Onondaga Pottery Company; William McGaghie, Chicago, Ill.—R. R. Donnelly and Sons.

Education • • •

Committee to Advise on Defense Training

To assist in the task of utilizing the facilities of engineering schools and colleges in the emergency training of workers for defense industries, John W. Studebaker, United States commissioner of education, has appointed a special advisory committee composed as follows: chairman, Andrey A. Potter, dean of engineering, Purdue University; R. E. Doherty (A'16, F'39) president, Carnegie Institute of Technology; Gibb Gilchrist, dean of engineering, Texas Agricultural and Mechanical College; H. P. Hammond, dean of engineering, Pennsylvania State College; W. O. Hotchkiss, president, Rensselaer Polytechnic Institute; R. S. McBride, consulting engineer; Thorndike Saville, dean of engineering, New York University; C. C. Williams, president, Lehigh University; B. M. Woods, chairman, department of mechanical engineering, University of California; F. L. Bishop, secretary, Society for the Promotion of Engineering Education; Allen W. Horton, Jr., United States Office of Education (secretary).

It will be the task of this committee to aid in devising ways and means of best utilizing the teaching staffs and plants of technical schools in presenting special courses, not necessarily for students of collegiate grade, designed to furnish special skills needed in carrying out the defense program. Funds for this purpose have already been appropriated.

Educators See New Electronic and Lighting Devices

In an all-day conference held October 18 at the lamp division, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J., more than 100 educators from eastern engineering schools were shown some of the latest developments in electronic and illuminating equipment achieved by research workers and engineers of that company. The program included talks by A. E. Snyder, Doctor Charles M. Slack, I. E. Mouromtseff (A'25), Doctor Harvey C. Rentschler, Doctor John W. Marden, and Samuel G. Hibben

Letters to the Editor • • •

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Two-Phase Co-ordinates of a Three-Phase Circuit

To the Editor:

The 1939 AIEE TRANSACTIONS just reached the writer's desk a few days ago. It took almost exactly 100 days in its transit to Changting, its postmark at New York being January 29. The writer wants to thank the Institute officers for its delivery, as periodicals of this sort are a tremendous solace to Chinese educational institutions in their present struggle for existence.

On looking over the pages the attention of the writer fell on the very interesting paper of Kimbark on "Two-Phase Co-ordinates of a Three-Phase Circuit".[3] Three main points have been brought up by the different discussions, namely (1) the title, two-phase, (2) the coefficients of the transformation matrix, and (3) the possibility of avoiding mutual coupling between different axes. The writer would like to discuss these points in that order.

For a suitable title, the writer suggests the impersonal name "cylindrical co-ordinates". Early in 1929 the writer investigated the feasibility of representing three-phase circuits by three-dimensional vectors.[2] A very simple and useful vector, called the isoclinic unit vector and defined as

$$u = (1/\sqrt{3})(i+j+k)$$

was then brought to light.[2] A geometrical relation deducible from the method of representation is that the locus of the end of the vector denoting a general unbalanced three-phase quantity (voltage or current) without harmonics is an ellipse. On eliminating the component in the u direction—that is, the zero-sequence component, the ellipse lies on a plane—called the fundamental plane—normal to u. The major and the minor axes of this ellipse are respectively equal to the sum and the difference of suitably defined positive- and negative-sequence components. Further, when harmonics exist, the locus lies on a right cylinder having u as its axis, the cross section of the cylinder being determined by the positive- and the negative-sequence components, together with the harmonics not multiples of the third. It is thus seen that the co-ordinates discussed by Kimbark bear a close relationship with the method of representation just given. An appropriate impersonal name is perhaps "cylindrical co-ordinates" or "elliptic co-ordinates", preferably the former.

Coming to the second point, the writer recalls that while attempting to find the properties of the ellipse, he transformed the co-ordinate axes from i, j, k to an orthogonal right-handed system, u, v, w, having direction cosines as follows:[1]

	i	j	k
u	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$
v	$\frac{\sqrt{2}}{\sqrt{3}}$	$-\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$
w	0	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

These nine coefficients may be written as a matrix or a dyadic or a tensor, according to one's taste. They will be recognized to be those listed in the discussion by Boyajian[1] of Kimbark's paper, multiplied by different factors for each row. Stated in another way, the matrices listed by Boyajian give the direction *numbers* while the matrix given previously contains the direction *cosines*. In terms of the method of repre-

sentation proposed by the writer, the co-ordinate axes discussed by Kimbark are obtained from the phase axes i, j, k by a simple rotation, changing i to u, j to v, and k to w.

As to the difficulty in remembering these coefficients, the writer offers two ways out: one geometrical and the other algebraic, both in conformity with a unified theory of three-phase-circuit analysis, namely that based on space vectors and dyadics.[4] In the 1929 paper, the writer picked up these coefficients, not by a hit-or-miss process, but through their geometrical simplicity. As mentioned before, a positive- and a negative-sequence system will combine to form an ellipse on the fundamental plane. This plane being normal to the isoclinic direction, the latter direction, having direction cosines all equal to $1/\sqrt{3}$, is taken as one of the references. On the fundamental plane there are three outstanding lines, namely its intersections with the co-ordinate planes jk, ki, and ij. The line of intersection $(j-k)$ between the jk plane and the fundamental plane has direction cosines 0, $1/\sqrt{2}$, $-1/\sqrt{2}$, which may then be taken as the w direction. Finally, the v direction is chosen perpendicular to both u and w forming with w,u a right-handed orthogonal system. In vector language, v is obtained as the vector product of w by u, that is,

$$v = w \times u$$

Hence the direction cosines as given.

The algebraic method is to obtain the transformations through the use of the unit vectors u, f, b, denoting symmetrical co-ordinates. These have been defined by the writer as:

$$u = \frac{i+j+k}{\sqrt{3}}, \quad f = \frac{i+a^2j+ak}{\sqrt{3}}, \quad b = \frac{i+aj+a^2k}{\sqrt{3}},$$

wherein a and a^2 are the two complex cube roots of unity as usual. The appearance of $\sqrt{3}$ in the denominators insure the vectors to be of unit length. To change to "cylindrical co-ordinates", u is defined as before and v and w are defined as the real part and the imaginary part of f or b, since they are conjugate, through the simple relations:

$$v = (f+b)/\sqrt{2}$$

and

$$w = j(f-b)/\sqrt{2}$$

The divisor $\sqrt{2}$ is again introduced to make these vectors unit in length while the j is to make w real. It is of interest to compare these definitions with those given by the writer in deriving the axes for "two-reaction theory",[4] Thus corresponding to the stationary symmetrical co-ordinates, u, f, b, we have the rotating symmetrical co-ordinates u, s, n defined as: u (same as before), $s = e^{jwt}f$, and $n = e^{-jwt}b$, s being thus a unit vector rotating at synchronous speed and n one rotating at negative synchronous speed. Knowing these complex vectors s and n, the d, q co-ordinates are simple the real and the imaginary parts of s or n. Thus we define: u (same as always)

$$d = (s+n)/\sqrt{2}$$

and

$$q = j(s-n)/\sqrt{2}$$

These show in a striking way the close relationship between u, f, b, and u, v, w on the one hand and u,s, n and u, d, q on the other. It may also be pointed out that from i, j, k (the phase axes), u, f, b and u, s, n are obtained by unitary transformations while u, v, w and u, d, q are obtained by orthogonal transformations. All four have u as a common axis.

Regarding the possibility of avoiding mutual coupling by properly choosing the axes, it is feared that complete elimination is in general impracticable if not impossible. This seems to be the verdict of the theory based either on dyadics or on matrices. In case of partial elimination, there is usually more than one possibility; for example, in addition to the four systems, the following orthogonal transformation will also eliminate coupling partly, in case the network is symmetrical with respect to one phase:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

As for the general bilateral static network typified by a self-transposed impedance dyadic, it is possible to transform it so that there is no coupling between any axes. The transformation, unlike those for partial elimination, is unique. To determine the transformation, Hamilton-Cayley identity and the three scalar invariants of a dyadic have to be used.[4] In fact, a self-transposed dyadic is known as a "right tensor" characterized by an ellipsoid with three principal axes. When referred to these axes, no coupling exists. From the viewpoint of circuit analysis the difficulty seems to be that each part of the network has its own ellipsoid with different sets of principal axes. It would be very helpful if some one could work out a scheme by which different axes might be used in the same problem at the same time.

In concluding, the writer would like to summarize the advantages of using the transformation matrix for cylindrical co-ordinates as given in this communication as follows:

(1). The values of the coefficients are unique, being the direction cosines (not direction numbers) of axes easily remembered from the geometrical or the algebraic exposition already given.

(2). The transformation is a rotation of space; that is, the transformation using direction cosines may be so interpreted. Hence its inverse (or reciprocal) is equal to its transpose.[4] The determinant of the matrix is 1.

(3). The same transformation is used for either current or voltage and yet the expression of power remains both invariant in form and in magnitude. No extra numerical factor occurs.

(4). A simple and unified correlation exists among the four most useful systems known to the profession thus far.

(5). The zero-sequence impedance, that is, Z_{00} or Z_{uu}, has the same value in all four transformations, u, f, b; u, s, n; u, v, w; and u, d, q.

In mentioning these advantages, the writer is aware of the fact that the magnitudes of the quantities in the u, v, w directions are not equal to the zero-, the sum and the difference of the positive- and the negative-sequence components as defined by Fortescue. This deserves further comment. It is much like the rationalization of electrical units. In other words, we have here to decide whether we should like to have units in the different axes of the same length, hence the numerics to have extra factors, *or* the numerics to be free from surds and the units to be different in lengths. It is hoped that the whole theory will be more thoroughly examined in this respect by a larger number of persons to see if we can all agree on definitions that will take in as many of the advantages as possible, still preserving a teachable and unified theory. In time an international committee on standardization, probably the International Electrotechnical Commission, should be asked to decide what the best definitions are. Let us all remember the irrational 4π and profit by its history.

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A. Pen-Tung Sah (A'35, M'36)

(President, National University of Amoy, Changting, China)

"Electromagnetic Problems in Electrical Engineering"

To the Editor:

I am much indebted to Mr. Higgins for his letter on pages 246–7 of the June issue of Electrical Engineering, in which he points out an error in the solution I gave some years ago for the problem of the magnetic field due to a long straight permeable wire in air. Higgins is quite right in his assertion that the vector potentials inside and outside the wire must reduce to equality at the surface of the wire, that is, the vector potential is continuous at the interface. I was evidently led to my erroneous sentence, quoted from page 276 of my book, by the necessity of maintaining the tangential magnetizing force continuous at the interface, completely overlooking the fact that my statement was inconsistent with the requirement of continuity in the vector potential.

It is to be noted, however, that Higgins has made a serious error in his attempt to provide the corrected solution. His condition (c) is virtually a statement that the tangential induction is continuous at the interface, which is obviously quite incorrect for a permeable wire. In reality it is the magnetizing force that is continuous and the induction discontinuous.

The correct solution is as follows. Defining the vector potential $\boldsymbol{A}$ such that

$$\text{curl } \boldsymbol{A} = \boldsymbol{B} = \mu \boldsymbol{H}, \tag{1}$$

and satisfying the circuital relation

$$\text{curl } \boldsymbol{H} = 4\pi\delta \tag{2}$$

between the vectors of magnetizing force $\boldsymbol{H}$ and current density δ, together with the further condition that $\boldsymbol{A}$ is a solenoidal vector, namely,

$$\text{div } \boldsymbol{A} = 0, \tag{3}$$

leads to

$$\nabla^2 A = -4\pi\mu\delta \qquad (4)$$

within a current-occupied region and

$$\nabla^2 A = 0 \qquad (5)$$

in a region free from current. We now seek expressions for A suitable for each region, satisfying the necessary condition of continuity at the surfaces of separation between the various regions and containing constants that can be found from the usual conditions of continuity in normal induction and tangential magnetizing force at those surfaces. All this is quite general and will be found in detail in any textbook on vector analysis.

In the present two-dimensional problem the lines of vector potential inside and outside the wire are parallel to its axis and there is obvious symmetry around that axis. If A_i is the vector potential inside and A_e that outside, both being functions of r only, then it is easy to deduce that (4) and (5) become

$$\frac{\partial^2 A_i}{\partial r^2} + \frac{1}{r}\frac{\partial A_i}{\partial r} = -4\pi\mu\delta$$

when $r < a$;

and

$$\frac{\partial^2 A_e}{\partial r^2} + \frac{1}{r}\frac{\partial A_e}{\partial r} = 0$$

when $r > a$,

where $\delta = I/\pi a^2$; these are the conditions (a) and (b) of Higgins's letter. Also $A_i = A_e$ when $r = a$ and A_i remains finite, which are conditions (d) and (e). Appropriate forms for A_i and A_e are

$$A_i = -\mu I\frac{r^2}{a^2}$$

$$A_e = C_3 \log r + C_4$$

as Higgins shows. It is also easy to show that in two dimensions the components of curl in (1) become

$$B_r = \partial A/r\partial\theta \text{ and } B_\theta = -\partial A/\partial r$$

in tangential and radial directions. In the case of a wire of circular section, A_i and A_e are independent of θ, so that the radial induction vanishes everywhere. At the surface of the wire the tangential magnetizing force is continuous; that is,

$$-\frac{1}{\mu}\frac{\partial A_i}{\partial r} = -\frac{\partial A_e}{\partial r} \text{ at } r = a$$

which replaces the incorrect condition (c) given by Higgins. Substituting the values found above for A_i and A_e gives $C_3 = -2I$ which, with the further condition that $A_i = A_e$ at $r = a$, makes $C_4 = 2I \log a - \mu I$. Hence finally

$$A_i = -\mu I\frac{r^2}{a^2}$$

when $r \leq a$

$$A_e = -2I\left(\log\frac{r}{a} + \frac{\mu}{2}\right)$$

when $r \geq a$

which differs from the value given in my book only in the constant term of A_i. Although my original expressions are incorrect to the extent of this constant they lead to no error in computing the magnetizing force or induction, since these depend on derivatives of vector potential and are in no way affected by the choice of constants required to adjust the continuity of vector potential at the interface. Inspection of the solution given by Higgins shows that his value for A_e must be incorrect since it is consistent with continuity in tangential induction at the surface of the wire, in complete contradiction of the physical facts of the problem.

B. Hague (M'30)
(Electrical engineering department, The University, Glasgow, Scotland)

A Simple Method of Calculating Power Factor

To the Editor:

From my observations and experience with utility companies, there seems to be a definite need among engineers whose work deals with power-system operation for a satisfactory method for the calculation of power factor from kilowatts and kilovolt-amperes. Since this fundamental calculation must be made hundreds of times daily in this type of work, a method, in order to be called satisfactory, must be simple and direct and not require the use of cumbersome equipment. A table of trigonometric functions may be used to advantage, but does not meet the latter requirement.

A method having the advantages mentioned is described herein. It is very simple and direct and may be performed with the aid of any slide rule having the standard A, B, C, D, and CI scales. Normally only one setting of the slide is necessary.

Let

P = active power in kilowatts
Q = reactive power in kilovolt-amperes
PF = power factor

METHOD

1. Set Q on the C scale opposite P on the D scale.

2. Note reading on the A scale opposite the index of the B scale. This reading is equal to $(P/Q)^2$. Since P/Q and also its square may be either greater or less than unity, the decimal point must be located carefully.

3. Mentally add to this reading unity (1.00), and set the indicator to this value on the A scale.

4. Read the power factor, PF, at the indicator hairline on the CI scale.

THEORY

Consider the following expression for power factor:

$$PF = \frac{P}{\sqrt{P^2+Q^2}}$$

Rearranging

$$PF = \frac{(P/Q)}{\sqrt{1+(P/Q)^2}}$$

$$= \text{reciprocal of } \frac{\sqrt{1+(P/Q)^2}}{(P/Q)}$$

The ratio P/Q is obtained in step 1. The reading on scale A is the square of this ratio (step 2). When unity (1.00) is added, the value of the expression under the radical is obtained. The numerator of the fraction is represented by the position on scale C of the indicator hairline when set to the value $1+(P/Q)^2$ on scale A (step 3). Now the denominator of the fraction P/Q has been obtained already on scale D opposite the C-scale index. The value of the whole fraction is the difference logarithmically between the numerator and the denominator. This difference is represented by the point on scale C under the hairline of the indicator. Since the reciprocal of this fraction is the power factor, it may be read at once on the CI scale.

A few examples are given illustrative of the most important points in connection with this method. In some cases, such as example 2, the slide must be reset to make the final indication fall on the scale.

Example 1.

$P = 4{,}000$ kw
$Q = 3{,}000$ kva (reactive)

1. Set 3,000 on scale C opposite 4,000 on scale D.

2. Read 1.78 on scale A opposite the left-hand index of scale B.

3. Unity added to 1.78 is 2.78. Set the indicator to 2.78 on the left-hand end of scale A.

4. Read $PF = 0.800$ on the CI scale at the indicator hairline.

Example 2.

$P = 2{,}400$ kw
$Q = 700$ kva (reactive)

1. Set 700 on scale C opposite 2,400 on scale D.

2. Read 11.76 on scale A opposite the right-hand index of scale B.

3. Unity added to 11.76 is 12.76. The slide as now set occupies the wrong portion of the rule to give a reading on the CI scale. Therefore, using the indicator to mark the point opposite the index, shift the slide to the right until the left-hand index is at the indicator hairline (11.76 on scale A). Now reset the indicator to 12.76 on the right-hand half of scale A.

4. Read $PF = 0.960$ on the CI scale.

Example 3.

$P = 52$ kw
$Q = 675$ kva (reactive)

1. Set 675 on scale C opposite 52 on scale D.

2. Read 0.00593 on scale A opposite the right-hand index of scale B.

3. Unity added to 0.00593 is 1.00593. Set the indicator to 1.00593 on the left-hand end of scale A.

4. Read $PF = 0.0768$ on the CI scale. The cipher to the right of the decimal point must be inserted because there are two ciphers to the right of the decimal in the first number (0.00593) read on the A scale.

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An Operational Solution of Switching Problems

To the Editor:

I. The Heaviside calculus is a convenient means of determining the transient and steady-state current response in a network of impedances on which a set of voltages are imposed at time $t = 0$, providing thereafter no external agency acts on the network. If, however, at some later time

additional impedances and potentials are inserted or original units removed, the resulting current distribution cannot be obtained directly. Rather, the switching actions producing the alterations must be simulated by fictitious potentials, the current distribution due to these found, and this latter then combined with that produced by the original driving voltages. This is a clumsy technique; archaic, time consuming, lacking in elegance. The method presented in this paper eliminates the need of these imaginary voltages, thus enabling one to obtain the current response directly from the operational equation.

II. If at $t=0$ voltages are impressed upon a network of impedances devoid of currents the subsequent current flow in a branch of the circuit can be found at once. One seeks a solution* of

$$F(D)y=f(t) \tag{1}$$

which satisfies the boundary conditions

$$D^iy=0 \quad i=(0,1,2\ldots n-1) \text{ at } t=0 \tag{2}$$

The operational solution is

$$y=\frac{f(t)}{F(p)} \tag{3}$$

Consider next the problem of determining the subsequent current flow in a branch of a network of impedances when at the instant $t=0$ the driving potentials producing the currents present (either transient or steady-state) are removed. One must find a solution of

$$F(D)y=0 \tag{4}$$

which satisfies the boundary conditions

$$D^iy=C_i \quad i=(0,1,2\ldots n-1) \quad \text{at } t=0 \tag{5}$$

The required solution† is

$$y=P(t)-\frac{1}{F(p)}[F(D)P(t)] \tag{6a}$$

where

$$P(t)=C_0+C_1\frac{t}{1|}+C_2\frac{t^2}{2|}+\ldots+C_{n-1}\frac{t^{n-1}}{(n-1)|}$$

$$=\sum_{i=0}^{i=n-1}C_i\frac{t^i}{i|} \tag{6b}$$

Finally, consider the problem of finding the subsequent current flow in a branch of a network of impedances in which currents are flowing (either transient or steady-state) when at some instant $t=0$ the network is altered by the insertion of additional impedances, the removal of original impedances, the insertion of new driving potentials, the removal of old driving potentials, or any combination of such variations in the character of the network. The desired expression for the current is the solution of

$$F(D)y=f(t) \tag{7}$$

which satisfies the boundary conditions

$$D^iy=C_i \quad i=(0,1,2\ldots n-1) \quad \text{at } t=0 \tag{8}$$

We shall show that the solution is equations 3 plus 6a.

Note that equation 4 is a special form of equation 7; thus equation 6 is a solution of equation 7 as well as of equation 4. Again, since equation 7 is a linear differential equation, any sum of solutions is a solution; therefore equations 3 plus 6, or

$$y=\frac{f(t)}{F(p)}+\left\{P(t)-\frac{1}{F(p)}[F(D)P(t)]\right\} \tag{9}$$

is a solution of equation 7. Furthermore equation 9 satisfies the boundary conditions (equation 8) for we have

$$D^iy=D^i\frac{f(t)}{F(p)}+D^i\left\{P(t)-\frac{1}{F(p)}[F(D)P(t)]\right\}$$
$$=0(\text{by } 2)+C_i(\text{by } 5)$$
$$=C_i$$

Hence equation 9 or, more compactly,

$$y=P(t)+\frac{1}{F(p)}[f(t)-F(D)P(t)] \tag{10a}$$

where

$$P(t)=\sum_{i=0}^{i=n-1}C_i\frac{t^i}{i|} \tag{10b}$$

is the desired solution of

$$F(D)y=f(t) \tag{10c}$$

satisfying

$$D^iy=C_i \quad i=(0,1,2\ldots n-1) \text{ at } t=0 \tag{10d}$$

III. In a number of problems $P(t)$ is simply a constant C_0; if so, equation 10a can be considerably simplified. When $P(t)=C_0$ we will have $F(D)y$ in the form

$$F(D)y=\frac{dy}{dt}+y\cdot\text{constant}=\left[\frac{d}{dt}+k\right]y$$

and equation 10a becomes

$$y=C_0+\frac{1}{p+k}\left\{f(t)-\left[\frac{d}{dt}+k\right]C_0\right\}$$
$$=C_0+\frac{1}{p+k}f(t)-\frac{1}{(p+k)}C_0k$$
$$=\frac{1}{p+k}f(t)+C_0-C_0k\frac{1}{k}(1-\epsilon^{-kt})$$
$$=\frac{1}{p+k}f(t)+C_0\epsilon^{-kt} \tag{10A}$$

IV. In this section are worked several examples which serve to illustrate the ease of application and elegance of solution as compared with the method of simulating switching actions by imaginary voltages. The first is a rather trivial example which serves mainly to familiarize one with the notation.

Problem 1. To find the subsequent current y in the circuit of figure 1 which is in steady state when the switch is opened at $t=0$.

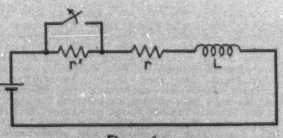

Figure 1

Solution. We must find y which satisfies

$$(r+r')y+L\frac{dy}{dt}=E;\ (r+r')y+Lpy=E;$$

$$y=\frac{E}{r+r'+Lp}$$

and the boundary condition

$$y=\frac{E}{r}=D^0y=C_0 \text{ at } t=0$$

The solution is given at once by equation 10A

$$y=\frac{1}{p+\dfrac{r+r'}{L}}\frac{E}{L}+\frac{E}{r}\epsilon^{-\frac{r+r'}{L}t}$$
$$=\frac{E}{L}\cdot\frac{L}{r+r'}\left(1-\epsilon^{-\frac{r+r'}{L}t}\right)+\frac{E}{r}\epsilon^{-\frac{r+r'}{L}t}$$
$$=\frac{E}{r(r+r')}\left(r+r'\epsilon^{-\frac{r+r'}{L}t}\right)$$

Problem 2. To find the subsequent current y in the circuit of figure 2 when switch

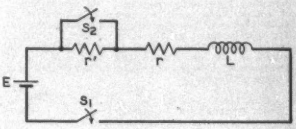

Figure 2

S_1 is closed at $t=0$ and S_2 at $t=T(t'=0=t-T)$.

Solution. We are to find y which satisfies

$$ry+L\frac{dy}{dt}=E;\ (r+Lp)y=E;\ y=\frac{E}{r+Lp}$$

and the boundary condition

$$y=\frac{E}{r+r'}\left(1-\epsilon^{-\frac{r+r'}{L}T}\right)=D^0y=C_0 \text{ at } t'=0$$

From (10A) we have

$$y=\frac{1}{p+\dfrac{r}{L}}\cdot\frac{E}{L}+\frac{E}{r+r'}\left(1-\epsilon^{-\frac{r+r'}{L}T}\right)\epsilon^{-\frac{r}{L}t'}$$
$$=\frac{E}{L}\frac{L}{r}\left(1-\epsilon^{-\frac{r}{L}t'}\right)+$$
$$\frac{E}{r+r'}\left(1-\epsilon^{-\frac{r+r'}{L}T}\right)\epsilon^{-\frac{r}{L}t'}$$
$$=\frac{E}{r}-\frac{Er'}{r(r+r')}\epsilon^{-\frac{r}{L}(t-T)}-\frac{E}{r+r'}\epsilon^{-\frac{r'}{L}T}\epsilon^{-\frac{r}{L}t}$$

APPENDIX

One must be careful to distinguish between $F(D)$ employed as a *linear operator* and $F(p)$ occurring in the operational formulas. The latter symbolism is familiar, the former possibly not so to many. We illustrate it by the following example. Let $F(D)\equiv\dfrac{d^3}{dt^3}+\dfrac{d}{dt}$ operate on ϵ^{at}; we have

$$F(D)\epsilon^{at}\equiv\left[\frac{d^3}{dt^3}+\frac{d}{dt}\right]\epsilon^{at}=a^3\epsilon^{at}+a\epsilon^{at}$$

* The notation is summarized in the appendix for the benefit of those to whom it may be unfamiliar.

† See "Linear Differential Equations," E. G. C. Poole, page 31.

With reference to the symbol $D^t y$ we note

$$D^0 y = y;\ D^1 y = \frac{dy}{dt};\ D^2 y = \frac{d^2 y}{dt^2};\ \text{etc.}$$

Finally, for the operator used in the solution of the problems

$$\frac{1}{p+k} = \frac{1}{k}(1-\epsilon^{-kt}).$$

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Books Received •

The following new books are among those recently received at the engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

PHENOMENA AT THE TEMPERATURE OF LIQUID HELIUM. (American Chemical Society Monograph Series No. 83.) By E. F. Burton, H. G. Smith, and J. O. Wilhelm. Reinhold Publishing Corporation, New York, 1940. 362 pages, diagrams, etc., 9½ by 6 inches, cloth, $6.00. Briefly describes liquefaction methods, the measurement of temperature, and the physical properties of liquid and solid helium; discusses superconductivity, specific heats at low temperatures, paramagnetism, temperatures below 1 degree Kelvin, the nature of the superconducting state, and the λ-transformation in liquid helium. Each chapter has a large bibliography.

ELECTRIC CIRCUITS. A First Course in Circuit Analysis for Electrical Engineers. (Principles of Electrical Engineering Series.) By members of the staff of the department of electrical engineering, Massachusetts Institute of Technology; a publication of the Technology Press, Massachusetts Institute of Technology; John Wiley and Sons, Inc., New York; Chapman and Hall, London, 1940. 782 pages, illustrated, 9½ by 6 inches, cloth, $7.50. The staff of the Department of Electrical Engineering at Massachusetts Institute of Technology has for some years been engaged in a program of revising as a unit substantially its entire presentation of the basic technological principles of electrical engineering. This volume, the first of a projected series covering this revised presentation, discusses circuit theory and analysis, with many problems. Appendixes contain tables of the electrical properties of metals, methods of solving linear algebraic equations, tables of units, standards, etc., and a selective bibliography.

APPLIED X RAYS. By G. L. Clark. Third edition. McGraw-Hill Book Company, New York, 1940. 674 pages, illustrated, 9 by 6 inches, cloth, $6.00. Intended for the industrial executive who wishes to know what X rays are, how they may be used, and the ways in which they can be applied to practical industrial problems. The first section discusses the general physics and applications of X radiation; the second covers the analysis of the ultimate structures of materials. Completely rewritten in consideration of the great advances since the previous edition.

ELECTRIC RAILWAYS IN INDIA. By Shiv Narayan. Printed by V. H. Barve at the Aryabhushan Press, Poona City, and published by Brij Narayan, 45 Wellesley Road, Poona, India, 1940. 128 pages, illustrated, 10 by 6½ inches, paper, Rs.4–8. Historical, statistical, and technical information on electric railways, vehicles, and trolley busses in India. Some space is devoted to electric traction in other countries. Glossary of electric traction terms.

ELEMENTS OF UTILITY RATE DETERMINATION. By J. M. Bryant and R. R. Herrmann. McGraw-Hill Book Company, New York, 1940. 464 pages, charts, tables, 9½ by 6 inches, cloth, $4.50. Aims to cover the field of public-utility rate determination, service, and discrimination from the viewpoint of the engineer and manager. Discusses reasons for the regulation of utility rates, describes the methods used to accomplish such regulation, and outlines the practical limitations involved.

GENERAL ENGINEERING HANDBOOK. Edited by C. E. O'Rourke. Second edition. McGraw-Hill Book Company, New York, 1940. 1120 pages, illustrated, 8½ by 5½ inches, flexible leather, $4.00. The purpose of this reference book is to present in one volume the fundamental data relating to all branches of engineering. The data are arranged in 19 sections: mathematics; mathematical tables; physical tables; engineering materials; theoretical mechanics; hydraulics; structural theory and design; plain and reinforced concrete; foundations; topographical and geodetic surveying; route surveying and earthwork; highways; municipal sanitation; machine elements; pumps, compressors, and hydraulic turbines; engineering thermodynamics; heating and air conditioning; fundamentals of electrical engineering; electrical measurements. This edition has been thoroughly revised and rearranged.

RECORDS AND RESEARCH IN ENGINEERING AND INDUSTRIAL SCIENCE. A Guide to the Production, Extraction, Integrating, Storekeeping, Circulation, and Translation of Technical Knowledge. By J. E. Holmstrom. Chapman and Hall, London, 1940. 302 pages, diagrams, etc., 9 by 5½ inches, cloth, 15s. Discusses the nature and methods of technical science and its practical applications; then describes the character, objects, and activities of experimental and technical organizations and societies. The succeeding chapters cover the various ways of searching technical literature, methods of indexing and filing, the expression and transmission of ideas, and the translation of foreign languages, with considerable reference to the author's personal experience. The qualifications and opportunities of the technician are also discussed.

TABLES OF CIRCULAR AND HYPERBOLIC SINES AND COSINES FOR RADIAN ARGUMENTS. Prepared by the Federal Works Agency, Work Projects Administration for the City of New York, as a Report of Official Project No. 665-97-3-10. Arnold N. Lowan, technical director, United States Bureau of Standards, Washington, D. C., 1939. 405 pages, 11 by 8 inches, cloth, $2.00. This volume, the third of a series of mathematical tables, gives circular and hyperbolic sines and cosines to nine places of decimals for a range of x from zero to 1.9999 at intervals of 0.0001. Some supplementary and conversion tables are included.

TELEVISION RECEIVING EQUIPMENT. By W. T. Cocking. The Wireless World (Iliffe and Sons, Ltd.), London. 298 pages, illustrated, 8 by 5 inches, cloth, 7s.6d. Explains the principles upon which the modern television receiver works, and deals with the design of its essential parts. Amplifiers, frequency-changers, detectors, time-bases, and sync separators are treated, and consideration is given to cathode-ray tubes and their deflecting systems, and to sound reception and fault finding.

MECHANISM AND THE KINEMATICS OF MACHINES. By W. Steeds. Longmans, Green and Company, London, New York, and Toronto, 1940. 319 pages, diagrams, etc., 9 by 5½ inches, cloth, 18s., $5.00. As a practical aid in the study of mechanisms as mechanical contrivances the author treats only of the kinematics of machines, omitting statics and dynamics. Specific mechanisms considered include straight-line actions, gearing, belts and chains, variable-speed gears, cams, universal joints, and ratchets. Exercises accompany each chapter.

STATISTICAL MECHANICS. By J. E. Mayer and M. G. Mayer. John Wiley and Sons, Inc., New York, 1940. 495 pages, diagrams, 9 by 6 inches, cloth, $5.50. Both classical and quantum mechanics are used as the basis of this elementary treatment of statistical mechanics. Fundamental statistical laws are derived, and the principles of application to various simple energy states discussed. Such special operations are combined in an appendix. Illustrative problems and glossary of symbols.

NOTIONS COMPLÉMENTAIRES SUR LES TUBES ELECTRONIQUES. By M. Chauvierre. Dunod, Paris, 1940. 205 pages, diagrams, etc., 8½ by 5½ inches, paper, 77 frs.; bound, 94 frs. Presents the fundamentals of electron-tube construction, operation, and application. Certain specific problems are considered fully. Graphical methods are used to a considerable extent.

INTRODUCTION TO ELECTRICITY AND OPTICS. By N. H. Frank. McGraw-Hill Book Company, 1940. 398 pages, diagrams, etc., 9 by 6 inches, cloth, $3.50. Intended for second-year students majoring in electrical engineering or physics, this textbook presents the fundamental laws of the electric and magnetic fields, and their elementary applications to circuits, to a study of the electrical and magnetic properties of matter, and to optics. Problems are included with each chapter.

NATIONAL PHYSICAL LABORATORY REPORT FOR THE YEAR 1939. Department of Scientific and Industrial Research. His Majesty's Stationery Office, London, 1940. 100 pages, tables, 10 by 6 inches, paper, 2s.6d. (obtainable from British Library of Information, 50 Rockefeller Plaza, New York, $0.75). In addition to general information concerning the laboratory and its work, this publication presents the reports of the William Froude Naval Laboratory and the departments of physics, electricity, radio, metrology, engineering, metallurgy, and aerodynamics, indicating the state of the current researches.

OUTLINE OF INDUSTRIAL RELATIONS POLICIES IN DEFENSE INDUSTRIES. Princeton University, Industrial Relations Section, Princeton, N. J., June 1940. 47 pages, 10 by 7 inches, paper, $0.75. Brief discussion and reported experiences are presented on: expansion of management organization, recruitment of production workers, training of skilled and semiskilled workers, wages and hours of work, employee-management co-operation in accelerated production. Selected bibliography.

STEAM POWER STATIONS. By G. A. Gaffert. Second edition. McGraw-Hill Book Company, New York, 1940. 592 pages, illustrated, 9 by 6 inches, cloth, $4.50. Chapters 1–17 deal with the construction and performance characteristics of the mechanical equipment, including fuels and feed water. The succeeding chapters, 18–24, cover plant economics and the integration of the machinery, with discussion of steam and binary-vapor cycles. Problems and short bibliographies.

THEORETICAL PHYSICS. Volume III. RELATIVITY AND QUANTUM DYNAMICS. EINSTEIN—PLANCK. By W. Wilson. E. P. Dutton and Company, New York, 1939. 276 pages, diagrams, etc., 9 by 5½ inches, cloth, $5.75. The final volume of this text, like the preceding volumes, presents physical theory as a coherent logical unity. The discussion of relativity passes from Einstein's special theory to the general theory. The development of the quantum theory starting with Planck, takes in wave mechanics, matrix mechanics, and electron theory. Contains a discussion of the analogy between geometrical optics and Hamiltonian dynamics, and its application to quantum dynamics.

MATHEMATICAL RECRATIONS AND ESSAYS. By W. W. Rouse Ball, revised by H. S. M. Coxeter. Eleventh edition. Macmillan and Company, Ltd., London; Macmillan Company, New York, 1939. 418 pages, illustrated, 8 by 5 inches, cloth, $2.25. Covers arithmetical and geometrical problems, magic squares, chess, and playing card recreations. Cryptographs and ciphers are discussed and the feats of various calculating prodigies briefly described. Several chapters have been enlarged in this edition; a chapter on polyhedra replaces one on mechanical problems, and string figures have been omitted.

BIBLIOGRAPHY ON INDUSTRIAL RADIOGRAPHY. Including Addenda I—April 1940. Document 1139. By H. R. Isenburger. American Documentation Institute, Washington, D. C., photographic copies, 8 by 6 inches, paper, $10.70. Contains references to over 200 articles on the industrial uses of radiography. The list supplements the bibliography published in St. John and Isenburger's "Industrial Radiography" and consists of articles published since the appearance in 1934, with a few omitted from the book. It covers the literature to April 1940.

ARTIFICIAL LIGHT AND ITS APPLICATION. Westinghouse Electric and Manufacturing Company, Westinghouse Lamp Division, Bloomfield, New Jersey, 1940. 296 pages, illustrated, 11 by 8½ inches, paper, apply. The history of artificial lighting is briefly surveyed, the units and methods of measuring light are described, and vision and color are discussed as an introduction to drafters which describe modern applications of lighting for all purposes, from ordinary home illumination to photographic work and germicidal radiations.

ELECTRIC CIRCUIT AND MACHINE EXPERIMENTS. By F. W. Hehre and J. A. Balmford. John Wiley and Sons, New York, 1940. 279 pages, diagrams, etc., 9 by 6 inches, paper, $2.00. Presents a set of experiments designed to cover elementary work in electric machines. The necessary apparatus, laboratory procedures, and safety precautions are described, and an outline of theory precedes each group of experiments.

ELECTROCAPILLARITY. By J. A. V. Butler. Chemical Publishing Company, New York, 1940. 208 pages, illustrated, 9 by 5½ inches, cloth, $5.00. Deals with potential differences at electrified interfaces, the origin and nature of the effects that arise therefrom, and with electrode equilibria and kinetics. Reviews the work of the past 15 years, touching many subjects, from the behavior of proteins to the passivity of metals.

ELECTRONIC PROCESSES IN IONIC CRYSTALS. By N. F. Mott and R. W. Gurney. Oxford University Press, New York; Clarendon Press, Oxford, England, 1940. 275 pages, illustrated, 10 by 6 inches, cloth, $5.50. Aims to develop the theory of the movement of electrons in ionic crystals, and to interpret experimental facts in terms of the theory. The Born theory of cohesion in ionic crystals and the Wagner-Schottky theory of ionic conductions in solids are described as an introduction. The succeeding discussions cover the absorption of light by ionic crystals, with the resulting photoconductivity and luminescence; the properties of semiconductors; and the insulating properties of nonconducting materials, including breakdown in high fields. Chemical reactions in solids are briefly considered in the final chapters.

Transactions

Preprint of Technical Papers Comprising Pages 603-642 of the 1940 Volume

Transient Starting Torques in Induction Motors

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Member ASME

L. A. KILGORE
MEMBER AIEE

Synopsis: A transient fundamental-frequency torque is shown to occur in the starting of all induction motors. For full-voltage starting on a general-purpose squirrel-cage motor, this torque may be as high as two or three times the pull-out torque. A consideration of such torques is particularly advisable for cases where induction motors are started and stopped frequently or continuously, since under such conditions mechanical failure of the motor or associated parts, gearing, couplings, etc., may occur if the stresses exceed the endurance limit of the material.

A method of analysis is given for calculating the transient electrical torques acting in the case of a locked rotor; the results obtained by means of this analysis are compared with test data obtained on a special locked-rotor test setup. A method is also given for calculating shaft torque from the electrical torque in the usual application. Test results also indicate that this method is satisfactory for practical use.

FOR many years engineers have used the average starting torque and pull-out torques of induction motors as the basis for mechanical design of shafts and couplings, not always realizing that high alternating torques existed at the moment of starting. So far as the authors are aware no one has published any practical analysis, or even a discussion of this problem.

The analysis and tests given in this paper show that when a motor is thrown on the line by the sudden closing of a switch, the contacts of which close simultaneously, a fundamental-frequency electrical torque which may be several times the pull-out torque, will be developed for the first few cycles. If the closing of the switch contacts of the several phases is not simultaneous, this alternating torque may be higher, and in the worst case of 90 electrical degrees lag, about 40 per cent higher alternating torques will exist.

The actual shaft and coupling torque will depend on the flexibility of the shaft and coupling and the inertia of the load and the motor. It is apparent that if the natural frequency of the mechanical system consisting of rotor, coupling, and load happens to be quite near the current supply frequency, the peak shaft torques may even exceed the electrical torque due to the resonance effect, particularly for high load inertias. Also, if the coupling has backlash or a non-linear torque-angle characteristic, an increase in torque may be had due to impact effects. Where the driven-load inertia is of the same order of magnitude or smaller than the motor inertia, a reduction in shaft torque is to be expected.

The fact that trouble from this source has been encountered only in exceptional instances may probably be explained as follows: (1) Usually the torsional natural frequency of the system is well below the current supply frequency so that most of the alternating torque is absorbed by the inertia of the rotor and is not transmitted to the shaft; (2) in most applications, starts and stops are relatively few so that a fatigue condition due to repeated loadings does not exist. Consequently, for such conditions, transient torques several times the endurance limit for indefinitely repeated loading may be absorbed without harm. Another way of explaining this is that the endurance curve for the shaft material (with stress concentration present) rises steeply as the number of cycles of repeated stress is reduced; (3) ample safety factors in shaft design based on experience are normally used; and (4) in most applications, the driven-load inertia is of the same order of magnitude or smaller than the motor inertia.

The mathematical analysis is carried out for the case of the locked rotor and yields the maximum torque which will be obtained at full voltage. For the case of reduced-voltage starting with an autotransformer or star-delta connection some flux may remain in the motor at the instant full voltage is applied with the result that even higher torques may occur. These latter conditions are, however, not considered in the present paper.

Electrical Torques

Before attempting a mathematical analysis of the problem, it is desirable to develop a physical picture of what is going on inside the machine under these transient conditions. It is simpler to think in terms of a two-phase machine, since the two windings are in space quadrature and have no mutual inductance. It will be shown in the appendix that the three-phase currents of a three-phase machine can be resolved into components acting on two quadrature axes (α and β).

In dealing with the transient torques in a machine, probably the most useful form of analysis is based on the difference in the products of fundamental current on each axis and fundamental air-gap flux on the axis in quadrature. In per unit notation[1]

$$T = i_{1\alpha} B_\beta - i_{1\beta} B_\alpha$$

or if the magnetizing current i_m on each axis is expressed in per unit notation, *the unit value being the current required to produce a flux sufficient to induce rated voltage at no load*, then:

$$T = i_{1\alpha} i_{m\beta} - i_{1\beta} i_{m\alpha} \qquad (1)$$

The sudden application of an alternating voltage to a reactive circuit will produce a transient asymmetrical flux and current depending on the point on the voltage wave at which the switch is closed.

The fundamental-frequency transient torque results from the reaction of the asymmetrical flux on one axis with the

Paper 40-100, recommended by the AIEE committee on electrical machinery, and presented at the AIEE summer convention, Swampscott, Mass., June 24-28, 1940. Manuscript submitted October 6, 1939; made available for preprinting April 22, 1940.

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The authors wish to express their appreciation to E. C. Whitney for his assistance in carrying out the analysis for electrical torques developed in this paper.

1. For all numbered references, see list at end of paper.

alternating current on the other, and also to the reaction of the asymmetrical current on one axis acting on the alternating flux in the other. The asymmetrical flux and the associated fundamental torque decay slowly, since these depend on the magnetizing inductance. The asymmetrical current and its associated fundamental torque decay rapidly since these depend on the leakage inductances. The torque components due to asymmetrical current and to asymmetrical flux are initially equal and of opposite sign.

The mathematical analysis is given in appendix *B* for the case of a locked rotor. The actual case of the machine coming up to speed becomes much more involved. However, the peak of this alternating shaft torque (except where exact resonance is approached) comes within the first few cycles and in this time the rotor will not have attained more than a few per cent speed and the effects of rotation on the transient currents and flux are negligible.

The results of this analysis of transient locked rotor torques are given in equation 11 in terms of the starting torque and locked power factor, for the case of simultaneous application of voltage to all phases.

For small machines, or larger high-torque machines, where the locked power factor ($\cos \phi$) is not less than 0.3, the component of alternating torque due to the asymmetrical current dies out so rapidly as to be negligible and the peak electrical torque may be obtained by neglecting the terms involving λ_2, which gives:

$$T_{1m} = T_s \left(1 + \frac{1}{\cos \phi}\right) \qquad (2)$$

For a large motor with low locked power factor the component due to the asymmetrical current decays more slowly. The resultant alternating torque starts at zero and builds up to a maximum in a few cycles, and the peak electrical torque will still be approximately that given by equation 2.

These equations apply only when there is simultaneous voltage application on all three phases. Such a condition is often difficult to obtain with actual switches or contactors. For this reason a second analysis was carried out by assuming that the switch was closed on one phase of the equivalent two-phase machine 90 electrical degrees (or 0.004 second at 60 cycles) later than on the other phase. On the three-phase machine this would mean that the third phase was closed 90 electrical degrees after the closure of the second phase. The results of this analysis are given in equation 12. Again neglecting terms involving λ_2 the peak electrical torque becomes:

$$T_{2m} = T_s \left(1 + \frac{\sqrt{2}}{\cos \phi}\right) \qquad (3)$$

Values of peak torque found for such conditions are around 20 to 40 per cent higher than those obtained on the assumption of simultaneous voltage application.

Figure 1. Test setup for measuring electrical torques

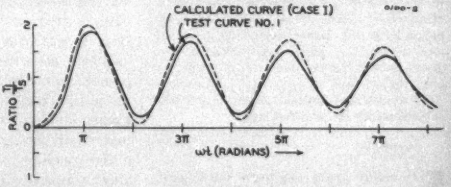

Figure 2. Comparison of test and calculated torque curves for typical high-torque induction motor

A physical explanation of the increased torque due to closing the last phase 90 degrees later may be had, by considering that this may result in maximum asymmetrical flux in each of the two axes which gives a resultant asymmetrical flux $\sqrt{2}$ times the maximum value on one axis.

Tests to Determine Electrical Torques

In order to check up on the theoretical work, a special locked-rotor test arrangement (figure 1) so designed as to record transient torques was used. Essentially, it consists of an arm attached to the motor shaft and held at its end by a thin tool-steel bar. Under the action of pulsating torques, this tool-steel bar is stretched or contracted, these transient movements being recorded on an oscillograph by means of a magnetic strain gauge.[2] By using a tool-steel bar, a fairly high natural frequency, relative to the current supply frequency, was obtained. The relation between rotor torque and oscillograph-beam deflection is established by a static calibration.

In figure 2 a typical curve of transient starting torque obtained on a high-resistance induction motor is shown by the full lines. It may be seen that this consists essentially of a pulsating component at the current supply frequency which dies out after a time. For comparison, a calculated curve obtained from equation 11 is also shown.

A summary of ratios of maximum torque T_m to nominal starting torque T_s obtained on various rotors at different frequencies (so that $\cos \phi$ varied from about 0.6 to 0.95) is shown in figure 3. It may be seen that while there is considerable scatter in the results, most of the test points occur between the limits of the curves defined by the approximate equations 2 and 3, with the latter equation yielding an approximation to the upper limit.

Transient Shaft Torques

General Method—Linear Couplings

The preceding discussion has been primarily concerned with the transient electrical torques acting on the rotor at the instant of starting. In most cases, however, the designer is mainly concerned with the transient shaft torques, since on these depends the design of the mechanical parts. As mentioned before, these shaft torques depend not only on the electrical torque, but also on the other characteristics of the drive including rotor and load inertias, flexibility of shaft-coupling system, and in certain cases, the shape of the torque-angle characteristic of the coupling.

In many cases of practical interest, an induction motor is coupled to a heavy inertia load by means of a flexible coupling. An example of such construction is the roll-table drive used in continuous strip mills. In such cases the system

may usually be represented for purposes of analysis by a single degree-of-freedom system consisting of a mass, representing the motor, connected by a spring, representing the coupling and shaft flexibility, to a rigid body. This analysis will hold approximately where the equivalent driven-load inertia is large compared to that of the motor. As will be shown later, the results for this case may also be used when the load inertia is finite.

If we neglect damping, the known differential equation of motion for such a

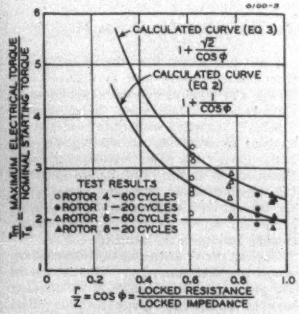

Figure 3. Comparison of test and calculated values of ratios between peak electrical torque and starting torque

system, assuming a coupling with a linear torque-angle characteristic is

$$I_m\frac{d^2\theta}{dt^2}+k\theta=F(t) \qquad (4)$$

The shaft torque may be determined by introducing $F(t)$ as given by equations 11 or 12 into equation 4 and integrating, the integration constants being determined from the initial conditions which require that when $t=0$, $\theta=0$, and $d\theta/dt=0$. Because of the rather complicated expression for $F(t)$, such an integration becomes very laborious and for this reason the following alternative method was used.

By using the principle of superposition, it may be shown that if damping is neglected, the angular displacement for the single degree of freedom system under consideration is given by:[3]

$$\theta=\frac{1}{\omega_n}\int_0^{t_1}\frac{F(t)}{I_m}\sin\,\omega_n(t_1-t)dt \qquad (5)$$

Application to High-Resistance Rotors

Unless the damping is unusually high, it is justifiable where high-resistance rotors are involved to neglect damping in practical systems where the natural frequency of the system is much less than the current supply frequency since in such cases the peak torque will occur within the first cycle of oscillation at the natural frequency.*

Assuming as before that the magnetizing reactance is very large compared to the rotor or stator resistance, the decrement factor λ_1, will be small compared to ω. Hence, the term $\epsilon^{-\lambda_1 t}$ may be taken as unity in the expression for $F(t)$, since during the first few cycles of applied voltage during which the maximum shaft torque occurs, this term will differ but little from unity. With this simplification, by integrating equation 5 the expression for shaft torque takes the form:

$$T=T_s\{1+\beta_1\epsilon^{-\lambda_2 t}+\beta_2\epsilon^{-\lambda_3 t}\sin(\omega t+\gamma_3)+\beta_3\times\sin(\omega_n t+\gamma_3)+\beta_4\sin(\omega t+\gamma_4)\} \qquad (6)$$

where β_1, β_2, β_3, β_4, γ_2, γ_3, γ_4, depend on ω/ω_n and ϕ.

For typical high-resistance rotors ($\cos\phi>0.3$), it may be assumed that the term $\epsilon^{-\lambda_2 t}$ dies out very rapidly during the first cycle of applied voltage, so that it may be neglected as far as any contribution to the peak torque is concerned. (The results, however, should not be applied when low-resistance rotors are being considered.) In addition, in practical cases where ω_n is not over say $\omega/2$, it may be assumed as a first approximation, that the phase angles γ_3 and γ_4 are such that the torque components β_3 and β_4 add directly. (This will yield results somewhat on the safe side, the closeness of the approximation being greater for smaller ratios of ω_n/ω.) With these simplifications, the peak shaft torque (for high-resistance rotors) becomes:

$$T_m=T_s\{1+\beta_3+\beta_4\} \qquad (7)$$

Values of the ratio T_m/T_s obtained by using this method for various values of $\cos\,\phi$ are plotted in figure 4 for simultaneous voltage application on both axes and in figure 5 for voltage application on the β axis 90 degrees later than on the α axis. It may be seen that the latter assumption yields definitely higher shaft torques. It should also be noted that peak transient shaft torques as high as four to five times the nominal starting torque may occur for cases where $\cos\,\phi=0.5$ and $\omega_n/\omega=0.5$. In utilizing these curves, it should be borne in mind that because of the assumptions made, the ratios T_m/T_s may be somewhat overestimated for the larger ratios of ω_n/ω.

An alternative method for obtaining an approximate solution is to take $\epsilon^{-\lambda_2 t}=0$ and $\epsilon^{-\lambda_3 t}=1$, as before, in the

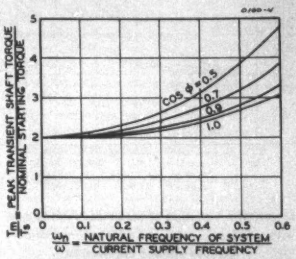
$\frac{T_m}{T_s}$ = PEAK TRANSIENT SHAFT TORQUE / NOMINAL STARTING TORQUE
COS ϕ=0.5
0.7
0.9
1.0
$\frac{\omega_n}{\omega}$ = NATURAL FREQUENCY OF SYSTEM / CURRENT SUPPLY FREQUENCY

Figure 4. Variation of maximum shaft torque with torsional natural frequency—simultaneous voltage application

Infinite load inertia and simultaneous voltage application in all phases assumed

expressions for torque given by equation 11 or 12. These approximate expressions are then substituted for $F(t)$ in the differential equation (4) and the integration carried out. Assuming as before that the torque components at the natural frequency and at the current supply frequency add directly, peak torques somewhat lower than those given by the curves of figures 4 and 5 are obtained.

The previous discussion deals only with the case where the equivalent load inertia is infinite compared to that of the motor rotor. Where this is not the case, that is, if the load inertia is of the same order of magnitude as the motor inertia (a condition which frequently occurs in practice), a comparison of the differential equations for the two cases shows that the curves of figures 4 and 5 may still be used provided that the natural frequency is determined by using an equivalent moment of inertia

$$I_e=\frac{I_mI_r}{I_m+I_r}$$

instead of I_m, and provided that the peak torque, thus found, is reduced in the ratio $I_r/(I_m+I_r)$.

Where the torque-angle characteristic of the coupling is nonlinear (as it is in many practical couplings) the differential equation (equation 4) will still apply if the constant k is replaced by a function $f(\theta)$ which represents the torque-angle characteristic of the coupling. Usually an analytical solution of this

* When operating with a natural frequency not far from the supply frequency, damping should be considered for an accurate solution.

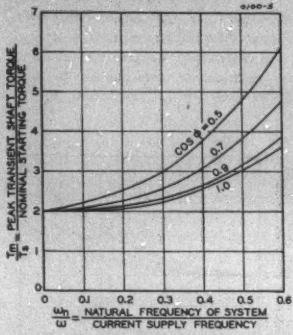

Figure 5. Variation of maximum shaft torque with torsional natural frequency—nonsimultaneous voltage application

Infinite load inertia and voltage application β axis 90 electrical degrees later than on α axis

modified equation is impractical and in such cases a numerical solution* has given good results when compared with actual test values.

The peak shaft torques obtained by using the methods of calculation outlined herein have been compared with the results of actual torque measurements on a typical high-resistance induction motor coupled to a heavy inertia load by means of a flexible coupling. The torques were measured by means of a magnetic strain gauge so mounted as to measure shaft twist, the results being recorded on an oscillograph. The tests were carried out by using a number of different makes of flexible couplings. Although a complete discussion of these results is beyond the scope of the present paper, it may be mentioned that the results indicate that the methods of calculation developed herein for high-resistance rotors are satisfactory for practical application.

Low-Resistance Rotors

For low-resistance rotors the $\epsilon^{-\lambda_3 t}$ term in equations 11 or 12 of appendix B cannot be neglected. In the first instant, $\epsilon^{-\lambda_3 t}$ is unity and the two components of alternating torque are found to cancel out. After a few cycles $\epsilon^{-\lambda_3 t}$ has decreased considerably and the alternating electrical torque approaches the value obtained from equations 11 and 12 by putting $\lambda_3 = 0$. Because the alternating torque builds up slowly an approximation to the peak torque should be had by adding directly (1) the shaft torque component at the natural frequency (produced by the impact effect of the average electrical torque applied in the first instant after starting) and (2) the torque component at fundamental frequency due to the alternating electrical torque. Where the load inertia is large, the first of these components will be about twice the average electrical torque in the first instant after starting. Where the ratio ω_n/ω is not low, it would appear that a rough estimate of this average torque could be obtained from equations 11 and 12 by taking $\epsilon^{-\lambda_3 t}$ as unity and neglecting the trigonometric terms. This gives an average electrical torque of $2T_s$ and $(1+\pi/2)T_s$ for the simultaneous and nonsimultaneous cases respectively, with resulting peak shaft torques of $4T_s$ and $(2+\pi)T_s$ due to the impact effect for the two cases. It should be noted that these values may be somewhat too high for the lower values of ω_n/ω and for very low values (say 0.1 or less) the peak impact torque may be taken as $2T_s$. To this must be added the fundamental-frequency shaft torque component due to the alternating electrical torque which is $\pm 1/(\omega^2/\omega_n^2 - 1) \cos \phi$ or $\pm \sqrt{2}/(\omega^2/\omega_n^2 - 1) \cos \phi$ for the simultaneous and nonsimultaneous cases, respectively, the negative sign being used if $\omega < \omega_n$. For a more accurate solution in any particular case equations 11 or 12 may be taken as the expressions for $F(t)$ in equation 5 and the integration carried out. The fact that mechanical damping is neglected when figuring the torques by these methods means that the calculated values of shaft torque may be somewhat too high particularly where the natural frequency is not far from the current supply frequency. Where the load inertia is not large compared to the motor inertia, these values should also be reduced in the ratio $I_r/(I_m + I_r)$ as discussed previously.

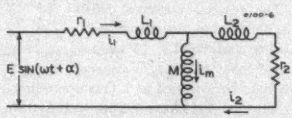

Figure 6. Equivalent circuit used in analysis

Conclusions

1. All induction motors started by sudden application of voltage will have transient fundamental-frequency electrical torques. If started at full voltage the peak electrical torque may be two times the pull-out torque or more.

2. The transient electrical torques can be calculated by equations 11 and 12. For a high-torque motor the peak electrical torque is given approximately by equations 3 and 4.

3. The test results (figure 3) show that the method of analysis is sufficiently accurate.

4. Mechanical torques for the common case where the torsional natural frequency of the mechanical system is well below the supply frequency are given by curves of figures 4 and 5 for high-torque motors. A method is also outlined for motors with low locked power factor.

Appendix A

The Equivalent Two-Phase Machine

Park[4] has shown how the currents of a three-phase machine may be resolved into direct- and quadrature-axis components on the two axes of the rotor. More recently Stanley[5] has given a somewhat more general analysis by resolving the three-phase currents along any two quadrature axes. Examination of the resulting equations of this method shows that they are exactly the same as for a simple two-phase machine, except for zero-sequence currents (that is, current flowing in the neutral).

One can arrive at this same conclusion by simple physical reasoning. The current in one phase may be thought of as dividing between the other two phases and this will be taken as one of the two-phase components. The second two-phase component will be the difference in the currents of the other two phases. So long as there are no neutral currents, the resultants of these two-phase components will be equal to the real three-phase current in any phase.

In order to establish the relation between the equivalent two-phase components, take I and E as the line currents and phase-to-neutral voltage of the three-phase machine. Then I and $3/2E$ are the current and voltage of the first phase of the equivalent two-phase machine, and $\sqrt{3}/2$ and $\sqrt{3}E$ are the current and voltage of the second phase. Either of these two phases could be used as the reference, but it is more convenient to use the first. For this case the equivalent two-phase current is the same as the three-phase current, but the two-phase voltage and the inductance and resistance values will be taken as $3/2$ times the three-phase line-to-neutral values.

The locked two-phase machine consists essentially of two independent transformers and the usual transformer equivalent circuit (figure 6) can be used accurately to represent current and voltage relations on each axis. The inductance coefficients L_1 and L_2 are the leakage inductances of the primary and secondary, and are numerically equal to the ohms reactance divided by $2\pi f$. M is the magnetizing inductance.

The secondary constants L_2 and r_2 are converted to the primary as is customary in all induction-motor calculations. Actually the secondary reactance and resistance are in most cases affected by eddy currents. The locked values of these constants will be used because they are correct for the fundamental-frequency currents, and the error is only in the decrement.

* See Timoshenko, reference 3, page 126, for an example of such a solution applied to a similar case.

Appendix B

Calculation of Transient Electrical Torques

In line with the discussion of appendix *A* the induction-motor winding is assumed divided into α and β components with axes at 90 degrees. Each component is represented by the equivalent circuit of figure 6. The voltage applied to the circuit is given in the general form $E \sin(\omega t+\alpha)$ and the parameter α may be so chosen for each axis that the voltages acting on the α and β axes will be 90 degrees apart. Referring to figure 6, assuming constant values of L_1, L_2, and M, the following differential equations hold:

$$(r_1+pL_1)i_1+pMi_m=E\sin(\omega t+\alpha)$$

$$(r_1+pL_1)i_1+(r_2+pL_2)i_2=E\sin(\omega t+\alpha) \quad (8)$$

$$i_1=i_2+i_m$$

The solution of these equations may be obtained either by using operational methods or by using the ordinary methods of solving differential equations, but the resulting expressions become rather cumbersome if all the terms are included. However, a simplification is possible since in practical motors the stator and rotor leakage inductances L_1 and L_2 are very small in comparison with the mutual inductance M, and hence may be neglected in certain expressions.*

The following boundary conditions hold:

at time $t=0$, $i_1=0$, $i_m=0$

and since no current is present when $t=0$

$$L_1pi_1+Mpi_m=E\sin\alpha$$

$$L_2pi_2-Mpi_m=0$$

In this manner we find:

$$i_1=I'\{(\sin\phi\cos\alpha-\cos\phi\sin\alpha)\epsilon^{-\lambda_1 t}+\sin(\omega t+\alpha-\phi)\} \quad (9)$$

$$i_m=I_m'[\epsilon^{-\lambda_1 t}\cos\alpha-\cos(\omega t+\alpha)] \quad (10)$$

The instantaneous electrical torque is obtained from equation 1. Two cases are assumed as follows:

Case I. Simultaneous application of voltage to both axes.

Case II. Application of voltage to β axis 90 degrees later than α axis to simulate effect of bouncing of switch contacts or irregularity in voltage application.

In practice it will be found almost impossible to apply voltage to all three phases at exactly the same instant; on the other hand the assumption of a 90-degree phase difference between voltage application to the two axes probably represents a fairly severe condition.

* An integration of these equations in which no terms were neglected has been carried out by E. H. Moss using numerical values for the constants M, L_1, and L_2 corresponding to an actual motor. This showed close agreement with the approximate method described.

CASE I—SIMULTANEOUS APPLICATION OF VOLTAGE TO BOTH AXES

In this case we use equations 9 and 10 taking $\alpha=0$ for the α axis and $\alpha=90$ degrees for β axis. Thus $i_{1\alpha}$ and $i_{m\alpha}$ are found from these equations by taking $\alpha=0$; $i_{1\beta}$ and $i_{m\beta}$ by taking $\alpha=90$ degrees. Using the expressions for $i_{1\alpha}$, $i_{m\alpha}$, $i_{1\beta}$, $i_{m\beta}$ thus found in (1) we obtain for the torque:

$$T_1=T_s\left\{1+\epsilon^{-\lambda_1 t}-\frac{\epsilon^{-\lambda_1 t}\cos(\omega t+\phi)+\epsilon^{-\lambda_1 t}\cos(\omega t-\phi)}{\cos\phi}\right\} \quad (11)$$

CASE II—APPLICATION OF VOLTAGE TO β AXIS 90° LATER THAN ON α AXIS TO SIMULATE EFFECT OF BOUNCING OF CONTACTS OR IRREGULARITY IN VOLTAGE APPLICATION

In this case we again use equations 9 and 10 and assume that the switch is thrown on the β axis 90 degrees later than on the α axis. Let $t=$time measured from instant switch is thrown on the α axis and $t_1=$time measured from instant switch is thrown on the β axis; then

$$t=t_1+\frac{\pi}{2\omega}$$

On the α axis we take $\alpha=0$ and $t=t_1+\pi/2\omega$ in equations 9 and 10 and thus obtain expressions for $i_{1\alpha}$ and $i_{m\alpha}$ in terms of t_1. The currents $i_1\beta$ and $i_{m\beta}$ on the β axis will be obtained from the same equations in this case by taking $\alpha=180$ degrees and $t=t_1$ to take into account the fact that there is a phase difference of 90 degrees between the voltages and a lag of 90 degrees between the time the switch is thrown on the two axes. Using these values of $i_{1\alpha}$, $i_{m\alpha}$, $i_{1\beta}$, and $i_{m\beta}$ in equation 1 the following expression for the electrical torque T_2 is obtained in terms of the time t_1:

$$T_2=T_s\left\{1+\tan\phi[(1-c)\epsilon^{-\lambda_1 t_1}+(\sqrt{1+c^2})\epsilon^{-\lambda_1 t_1}\sin(\omega t_1+\alpha_1)]+\frac{\sqrt{2}}{\cos\phi}\epsilon^{-\lambda_1 t_1}\sin\left(\omega t_1-\phi-\frac{\pi}{4}\right)\right\} \quad (12)$$

where

$$c=\epsilon^{-\frac{\lambda_1\pi}{2\omega}} \text{ and } \alpha_1=\tan^{-1}c.$$

Nomenclature

$\cos\phi=\dfrac{r}{\sqrt{x^2+r^2}}=$locked power factor

$E=$maximum value of applied voltage per phase

$f(\theta)=$function representing torque-angle characteristic of shaft-coupling system

i_1, $i_2=$stator and rotor phase currents

$i_m=$magnetizing current per phase

$i_{1\alpha}$, $i_{m\alpha}=$stator and magnetizing currents on α axis

$i_{1\beta}$, $i_{m\beta}=$stator and magnetizing currents on β axis

$I'=$peak value of steady-state locked stator current

$I_m'=$peak value of steady-state magnetizing current with rotor locked

I_m, $I_r=$moments of inertia of motor and driven load respectively

$I_s=I_mI_r/(I_m+I_r)=$equivalent moment of inertia of rotor-coupling-load system

$k=$spring constant of shaft-coupling system

L_1, $L_2=$stator and rotor leakage inductances per phase

$M=$mutual or magnetizing inductance

$p=d/dt=$derivative operator

r_1, $r_2=$stator and rotor resistances per phase

$r=r_1+r_2$

$T_1=$electrical torque assuming simultaneous voltage application on α and β axes

$T_{1m}=$maximum electrical torque assuming simultaneous voltage application

$T_2=$electrical torque assuming voltage application on β axis 90 degrees later than on α axis

$T_{2m}=$maximum electrical torque assuming voltage application on β axis 90 degrees later than on α axis

$T_m=$peak shaft torque or electrical torque

$T_s=$nominal starting torque

$T=$shaft torque

$t=$time

$\omega=2\pi$ times frequency of applied voltage

$\omega_n=2\pi$ times natural frequency of system consisting of motor rotor, coupling, and load

$x=x_1+x_2$

x_1, $x_2=$stator and rotor leakage reactances per phase

$x_m=$magnetizing reactance

λ_1, $\lambda_2=$decrement factors, $\lambda_1=\dfrac{\omega r_1r_2}{x_mr'}$; $\lambda_2=\dfrac{\omega r}{x}$

$\theta=$angular twist of shaft-coupling system between motor and load

β_1, β_2, β_3, $\beta_4=$transient shaft-torque components

γ_3, γ_3, $\gamma_4=$phase angles of corresponding transient shaft-torque components

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Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

A High-Speed Differential Relay for Generator Protection

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ASSOCIATE AIEE

RECENT papers have shown that high-speed differential relaying is considerably complicated by the presence of the d-c transient in asymmetrical through fault currents. This is particularly true of generator differential relaying, since an asymmetrical fault near the terminals of a generator provides a more severe d-c transient than at any other point on the system. The effect of the d-c component is to produce a false differential current during a through fault because of dissimilar performance of the current transformers, even though they may nominally be duplicate. When this false differential current reaches tripping proportions with respect to the restraining current, even for as short a time as one cycle with a high-speed relay, the relay problem becomes one of properly discriminating between a false and a true differential current of tripping magnitude.

Means have been provided in the relay described in this paper to make the above discrimination. The solution has been worked out in accordance with two general principles. First, the principle of variable-ratio characteristics has been used. This principle was first described in a paper[1] presented at the 1939 winter convention, wherein it is shown that when the restraining current is large, corresponding to a heavy external fault, the sensitivity of the relay should be reduced to allow for greater shortcomings in current-transformer performance. Second, both theory and tests have shown that when current-transformer saturation occurs, the false differential current tends to be out of phase with the restraining current. Consequently, the new relay has been made less sensitive at the higher restraint values when the differential current is out of phase with the restraining current. The new relay is shown in figure 1, together with the necessary external transformer. The relay and transformer together form a complete three-phase unit.

Paper 40-103, recommended by the AIEE committee on protective devices, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted November 8, 1939; made available for preprinting April 23, 1940.

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1. For numbered reference, see end of paper.

Principle of Operation

In order to analyze the principle of operation of the relay, a simplified diagram, showing the essential parts for one phase only, is desirable. This is shown in figure 2. The main current transformers on each side of the generator are shown connected to terminals 1, 2, and 3 of the transformer element which feeds the relay. The principal currents from the secondaries of the current transformers in the leads of the generator flow only in the external transformer, as will be noted in the diagram. The transformer element develops auxiliary current and voltage quantities for actuation of the relay element shown in the bottom part of the diagram. The relay element has been shown very schematically. It is composed of a balanced-beam element wherein the contacts are restrained from closing by split-phase voltage windings acting on the rear end of the beam, while the operating-coil magnetic circuit acting on the front end of the beam tends to close the contacts. Inspection of the transformer element of this diagram will show that it consists of two transformer elements, both on the same magnetic circuit. Coils A and B on the center leg of the punchings form one of these transformers, which will be referred to as the sum coil transformer, wherein a voltage is developed in winding B in response to the restraining currents, I_1 and I_3. Since the voltage developed by winding B energizes split-phase restraining coils as shown, it is evident at once that the restraining force on the back end of the beam will never pass through zero.

A possible difference current, I_2, is shown flowing in the differential connection of the main current transformers in the diagram. In the transformer element, this current must flow through the two primary coils, C_1 and C_2, of the second transformer unit on the magnetic core, this unit being referred to as the difference coil transformer. The coils, D_1 and D_2, form the secondary windings of this second unit. They are connected in series to energize the operating coil of the relay element.

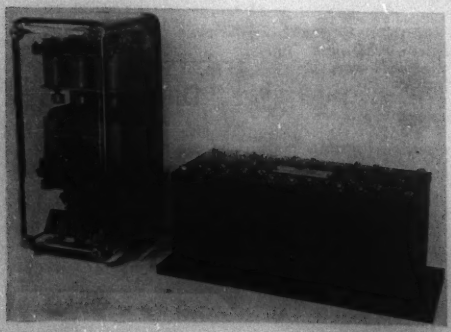


Figure 1 (left). Type HA ratio differential relay for generator protection

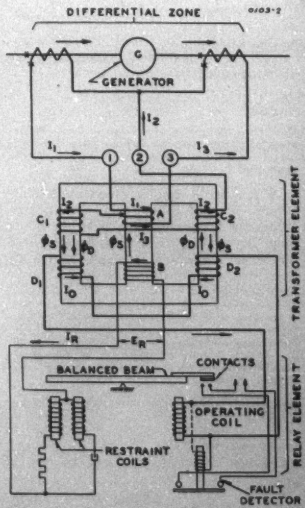


Figure 2. Schematic diagram of one relay element and auxiliary current transformer

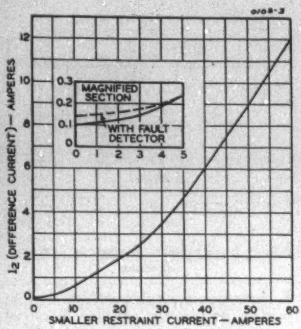


Figure 3. Typical operating characteristics of relay. Difference current, I_2, in phase with restraint current

Variable-Ratio Characteristics

Assuming in-phase currents, it will be seen from figure 2 that if the difference-coil current transformer is made to saturate to a greater extent at the higher currents than the sum-coil current transformer, and assuming linear relay characteristics, then it is obvious that a higher percentage of difference-coil current will be required to trip the relay contacts as the saturation of the difference-coil transformer is increased with respect to the sum-coil transformer. That is, as the restraint current is increased, the difference current to trip the relay will increase at a higher rate, thus resulting in the variable-ratio characteristic of figure 3. It will be noted from the curve that the minimum tripping current of the relay is 0.1 ampere in terms of the secondary, thus providing high sensitivity at no load on the machine. At 5 amperes restraint current, corresponding to full load, the difference current required to trip the relay is 0.25 ampere. This corresponds to a relay sensitivity of 5 per cent. From this point on, the variable-ratio characteristic of the relay is illustrated by the curve. For example, at 60 amperes restraint, a difference current to trip of 12 amperes represents 20 per cent unbalance. This indicates a decrease in sensitivity of the relay by a four-to-one range between normal and 12 times normal full-load current.

Phase-Angle Characteristics

Flux arrows have been drawn in the transformer element, figure 2, corresponding to the relative instantaneous direction of the currents, I_1, I_3, and I_4, as shown. The polarity of the connections of coils C_1, C_2, is such that ϕ_D, established by the difference current, I_3, flowing through coils, C_1 and C_2, circulates around the outer legs of the laminations. With symmetrical coil designs, there is no tendency for a portion of the flux, ϕ_D, to circulate through the middle leg of the transformer, since the two ends of this leg will be at the same magnetic potential with respect to ϕ_D. Thus, the flux, ϕ_D, established by the difference current, I_3, does not tend to establish directly a restraining-coil voltage, E_B, in coil B. The flux, ϕ_S, set up by the currents, I_1 and I_3, in coil A returning from top to bottom in the outer legs of the transformer as shown, has no tendency to induce operating-coil current in coils, D_1 and D_2, since, because of the polarity of connections of coils, D_1 and D_2, opposite voltages will be generated in these two coils by ϕ_S. From the above discussion,

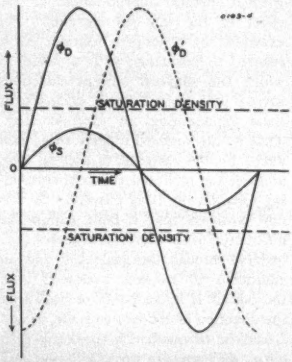


Figure 4. Flux waves in auxiliary current transformer

it is evident that if the magnetic material were of infinite permeability and never saturated regardless of the required flux density, the two transformer units, A/B and C_1C_2/D_1D_2 would have no effect upon each other and there would be no point to placing them both on the same magnetic structure. The fact that the magnetic material is not perfect, however, does introduce a mutual reaction between the two transformers, and this will be discussed.

Assume that the currents I_1, I_3, and I_4, of figure 2 are associated with the flux waves of figure 4, these flux waves being required to generate sufficient voltage in the respective coils to circulate the currents, I_6 and I_B, through the relay element. With I_3 in phase with I_1 and I_3, the power factor of the relay burden, both restraining and operating coils, may be so chosen that the fluxes, ϕ_S and ϕ_D, of figure 4 will be in phase as shown by the solid-line curves. If the quantities are so chosen, however, that the peak of the flux, ϕ_D, for the difference-current transformer, C_1C_2/D_1D_2, extends considerably into the zone of saturation, as shown in figure 4, then it will be noted that the peak flux, ϕ_S, for transformer A/B will be hard to obtain magnetically. That is, the return circuit for ϕ_S is the outer legs of the magnetic core in parallel, and these two outer legs are at that particular instant badly saturated by the difference transformer flux, ϕ_D. What this means is that a larger percentage of the sum-coil currents, I_1 and I_3, will go to magnetizing current, leaving a very small percentage to be transformed into restraining coil current, I_B, through the winding, B. (Casual inspection of figure 2 might indicate that the right-hand leg of the transformer punching might serve as a good return circuit for ϕ_S, since ϕ_S and ϕ_D are shown in opposite directions in this leg, thus reducing saturation and voiding the above argument. However, the argument is still valid, because at high saturation densities, there is not much difference between the amount of ampere turns required to reduce the flux density by a small increment and the amount of ampere turns to increase the flux density by the same small increment.) Thus, the solid-line flux, ϕ_S, of figure 4 is associated with a phase-angle condition in which it would be expected that the required difference current to trip the relay would be reduced because

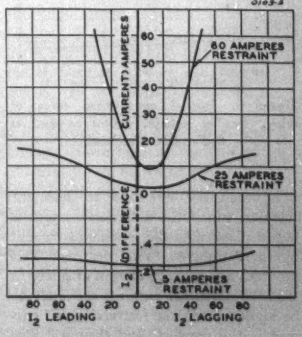


Figure 5. Typical phase-angle characteristics of relay

Phase angle in degrees of difference current with respect to smaller restraint current

of a reduced efficiency of the sum-coil transformer. If now the phase angle of the difference-coil current, I_2, is changed by 90 degrees with respect to the restraining current, I_1 and I_2, so that the difference-coil flux, ϕ_D, is moved by 90 degrees lagging, as shown by the broken-line curve, ϕ_D', of figure 4, it will be noted that the peak of sum-coil flux, ϕ_S, occurs at the instant that the difference-coil flux is passing through zero. It would be expected that under this condition the sum-coil transformer would operate more efficiently than in the previously described case, since the peak of its flux, ϕ_S, is more easily obtained when its return circuit is not saturated. The above discussion indicates that since the difference-coil transformer, through its flux requirements, is caused to saturate the return circuit for the sum-coil transformer, and since this saturation effect varies throughout the cycle, then the mutual reaction between the two transformers is variable, depending upon the phase-angle relationship between the sum-coil currents and the difference-coil current. By suitably proportioning the power factor and magnitude of the restraining-coil and operating-coil burdens of the relay element in conjunction with the transformer design, it was possible to arrive at a design in which the combination is less sensitive to difference-coil currents when these difference-coil currents are substantially out of phase with the restraining-coil currents.

The phase-angle characteristics of the relay are illustrated in figure 5. The curve shows that at 60 amperes restraint,

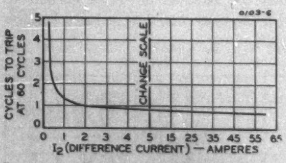


Figure 6. Typical current-time curve of relay. Smaller restraint current constant at five amperes (full load)

it is practically impossible to cause the relay to trip if the difference current is out of phase with the restraining current by more than 40 to 50 degrees. This provides a very large margin of safety in that the difference currents are likely to be highest when the restraining-coil current is the greatest, and they will also tend to be out of phase with the restraining-coil currents. At five amperes restraint, however, corresponding to full-load current, it should be noted that the phase-angle curve of the relay is substantially flat. This is desirable at load current, because there is no way of predicting just what the phase-angle relationship will be between a small internal fault current in a generator and the load current on the machine at the time.

When considering the phase-angle curves, it should be remembered that those curves where the restraint current exceeds 5 amperes represent through short-circuit conditions. For this reason, there is no cause for alarm in the indication that, for example, a 40-ampere differential current at 60 degrees lagging would not trip the relay at 60 amperes restraint. It would be impossible to obtain an internal short-circuit of 40 amperes magnitude and maintain a through current of 60 amperes for an external fault. In other words, these curves, except for the 5-ampere restraint curve, apply only to through fault conditions, and are not applicable to internal fault conditions without proper interpretation of the effect of the sum-coil currents. For example, the 60-ampere restraint curve referred to was taken with a setup in which the sum-coil current directions agreed with those shown in figure 2, these representing an external fault. That is, the sum-coil ampere turns produced by the currents, I_1 and I_2, were additive and produced a positive restraining force on the relay element. If it is now assumed that a fault within the differential zone draws 60 amperes (secondary) through the generator, and an additional 60 amperes back-feed from the bus, it is immediately obvious that the direction of the two currents, I_1 and I_2, will be reversed with respect to each other, their ampere turns will cancel in the sum-coil transformer, and there will be no restraint. Hence, the curve does not apply. For another example, let it be assumed that for the same internal fault, the generator current, I_1, is 60 amperes, but that the back-feed current I_2 reversed, is increased to 180 amperes. Then 60 amperes in one-half of the sum coil winding will cancel the effect of 60 amperes of the 180 amperes in the other half, leaving a net effect of 120 amperes in half of the winding, equivalent in effect to 60 amperes flowing in one coil and out of the other, as shown in figure 2. In this case, then, the 60-ampere curve of figure 5 would apply, although it should be remembered that the difference-coil current would be definitely fixed as the sum of the 60- and 180-ampere currents. This sum could conceivably be somewhat out of phase with the net restraining-coil current, but not enough to affect positive

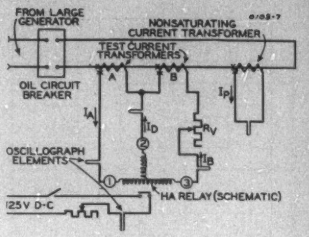


Figure 7. Schematic diagram of test connections

R_s represents a variable resistor used to produce more severe saturation in current transformer B

relay operation. Referring back to the curve for 5 amperes restraint, figure 5, it is possible that a light internal fault might occur which would not disturb the normal through load current of 5 amperes to any great extent, hence, this curve is applicable for internal faults as stated.

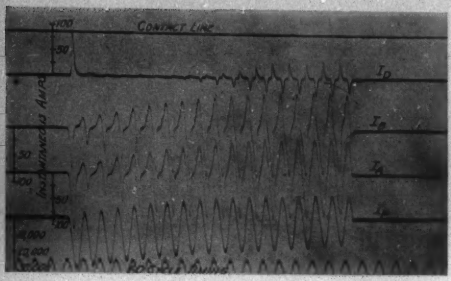
The time of operation of the relay is shown by the current-time curve of figure 6, wherein it is shown that the relay is a one-cycle relay.

Fault Detectors

The relay is provided with three small solenoid-type fault detectors, one for each of the elements, which may be used for those locations where the switchboard panel is subject to heavy jars or vibrations. At very light loads, the restraint occasioned by the load current may be negligible, and the extreme sensitivity of the differential element renders it subject to momentary closing of the contacts because of jars to the panel. In order to eliminate false tripping from this cause, the fault detectors are provided. Their coils are connected in parallel with the operating coils, and their contacts in series with the differential element contacts. Use of the fault detectors increases the minimum tripping current to 0.14 ampere, but has a negligible effect on the rest of the operating characteristics, figure 3.

Confirming Tests

Suitable tests have been made on the relay described. The essentials of the test connections are shown in figure 7. A large generator was used, so that d-c time constants up to T_a=0.14 were obtained. The resistor, R_s, of figure 7 was used to increase the burden on test transformer B so that the two transformers under test might be deliberately



Primary current, 10,800 amperes rms a-c component, T_a=0.11 second

Test transformer *A*: 1,000/5, 2.7 square inches iron; secondary circuit resistance —1.36 ohms

Test transformer *B*: 1,000/5, 2.53 square inches iron; secondary circuit resistance—4.04 ohms

Figure 8. Test oscillogram for external fault

unbalanced until failure of the relay occurred.

Figures 8 to 11 are typical oscillograms from a large number of tests. The essential data for each of these oscillograms are given in the captions.

In figure 8, representing an external fault, it is to be noted that there is an initial high peak of differential current which scales 87 amperes maximum instantaneous value. The normal output of transformers *A* and *B* would have been 54 amperes rms a-c component, if they held their ratio. Inspection of the traces representing the output of current transformers *A* and *B* reveals, however, that they do not hold their ratio, and that their output is severely limited by d-c saturation for the first few cycles. On this basis, it is obvious that the high-speed relay sustained a very high percentage unbalance for one peak without tripping, as the relay contact line indicates. A simple high-speed ratio-differential relay with the usual current coils would have tripped under this condition.

The peculiar wave shape of the differential current, shown in figure 8, warrants some discussion. The initial high peak is caused by the fact that current transformer *B* became thoroughly saturated by the d-c component a short interval of time before current transformer *A* became saturated. During the interval between the complete saturation of transformer *B* and transformer *A*, when transformer *B* alone was breaking down in ratio, transformer *A* was able to force the peak of differential current through the relay. When saturation was reached in both transformers, however, both of them performed very much as if they were air-core transformers, neither of them having sufficient capacity to hold their ratio with the burdens involved. During the time when both transformers were saturated, both the reduced capacity of the better current transformer as well as the impedance of the differential circuit effectively reduced the magnitude of the differential current. Thus, it will be noted that the difference current is inconsequential for approximately eight cycles after the initial high peak. After approximately eight cycles however, transformer *A*, having a better ratio of iron area to resistance burden, began the process of recovery from d-c saturation so that it was again able to perform somewhat better than transformer *B*. For this reason, a current began to reappear in the differential circuit.

As has been stated, the nominal output of both transformers would have been 54 amperes rms secondary, a-c component, if neither transformer had saturated, this value being derived from the 10,800-ampere symmetrical a-c component of the primary current and the ratio of the current transformers. In order to force this secondary current through the resistance burdens indicated, transformer *B* would have had to develop a flux density of 160,000 lines per square inch, and transformer *A* would have had to develop 51,000 lines of flux per square inch, calculated from the equation:

$$B_m = \frac{IR\,10^8}{4.44nfA}$$

where

B_m = maximum flux density in lines per square inch
n = number of secondary turns
f = frequency in cycles per second
A = cross-sectional area of the iron core in square inches
I = rms secondary amperes
R = total secondary circuit resistance

(This equation has been derived from the familiar transformer equation, $E=4.44nf\phi_m 10^{-8}$.) The flux density values indicated form a measure of the unbalance between the two current transformers, the flux densities for perfect a-c performance having a ratio of 3.14/1.

The wave form of the differential current in figure 8 was of sufficient interest to arouse speculation concerning what this differential current would look like if the impedance of the relay circuit were zero. In order to obtain data on this point, all three terminals of the relay were short-circuited together and the oscillogram of figure 9 was taken under the same conditions. (No contact line was desired in this case, since the relay element was short-circuited.) Figure 9 shows a similar high initial peak of differential current, which scales 101 amperes. Since there was no differential circuit impedance in this test to form a balancing action between the two transformers, the differential current did not subside to almost zero for several cycles, as in figure 8. The calibration of the oscillograph was the same for both tests.

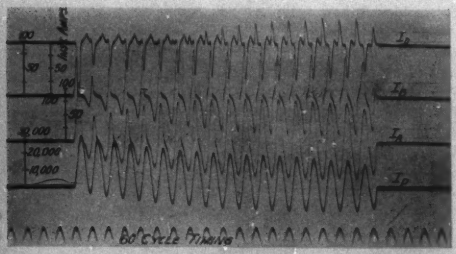


Figure 9. Test oscillogram for external fault

Conditions the same as for figure 8, except that the relay was short-circuited, terminal 1 to 2 to 3 (figure 7)

Figure 10 is an oscillogram for an internal fault with values as given in the caption. The internal fault was simulated by reversing the secondary connections of transformer *B* so that the total current of both transformers passed through the differential circuit of the relay. The time of operation of the relay is scaled from the contact line of the film to be approximately 0.6 cycle. Again, there was considerable saturation of the current transformers, particularly because of the d-c transient, yet prompt

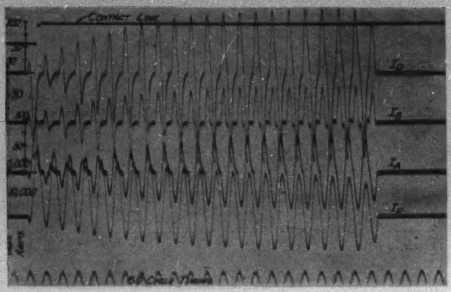


Figure 10. Test oscillogram for internal fault

Primary current, 10,900 amperes rms a-c component, $T_a = 0.123$ second

Test transformers as in figure 8 except secondary circuit resistance for current transformer *B* reduced to 2.44 ohms

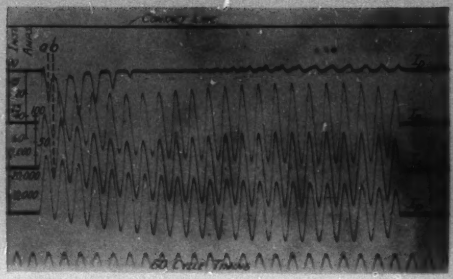


Figure 11. Test oscillogram for external fault

Primary current, 11,000 amperes rms a-c component, $T_a = 0.094$ second

Test transformer *A*: 4 primary, 800 secondary turns, 1,000/5, 4.8 square inches iron, secondary resistance (total) 1.31 ohms

Test transformer *B*: 1 primary, 200 secondary turns, 1,000/5, 1.7 square inches iron, secondary resistance (total) 1.18 ohms

operation of the relay was not affected.

Figure 11 shows another test for an external fault except that a different pair of current transformers was used with a different degree of unbalance, particularly with regard to the cross-sectional area of the iron in the test transformers. In this case, the calculated flux requirements for the a-c symmetrical component alone are as follows:

Transformer *A*—7,100 lines per square inch
Transformer *B*—71,600 lines per square inch

$$\text{Ratio } B/A = \frac{71,600}{7,100} = 10.2/1$$

In figure 11, the time of the first peak of differential current has been indicated by the dotted line, *a*, and it will be noted that this peak occurs earlier than the peaks of the two restraint, or sum coil, currents as indicated at *b*. This illustrates the meaning of the statement previously made that the differential current tends to be out of phase with the restraint current when the current transformers saturate during through fault conditions.

Summary of Test Results

The tests were made over a wide range of variation between current-transformer designs and loading, as has been indicated in part in figures 8 and 11. The purpose of this was to explore the range of possibilities of the new relay by exceeding the range normally to be expected. For example, it is felt that the conditions of figure 8 are more severe than would normally be expected for a reasonable application of generator differential protection. That is, it appears that the extreme importance of a large generator would justify the application of transformers whose a-c flux requirements for the maximum symmetrical external fault would not exceed the nominal saturation density of approximately 70,000 lines per square inch. Other tests, not described here, were made to cover the conditions imposed when a generator is connected to a double bus through two circuit breakers. In such an application, a heavy current may flow during an external fault from one bus to the other through the two circuit breakers connected to the generator. Such a current, flowing through the two current transformers per phase on the bus side of the generator, would materially increase the duty on them as compared to the duty imposed upon the current transformers in the neutral connection of the machine being protected. The relay performed satisfactorily in these tests.

Since it is obvious that there is a myriad of possibilities between different applications with regard to slight unbalances in iron area and secondary burden in current transformer circuits, the problem is how to best express the permissible variation in general terms. It has been found that the method of analysis used for the test of figures 8 and 11 is the most suitable; that is, where the flux density of the transformer is calculated showing the requirements for the maximum symmetrical current which will be experienced for an external fault. This method gives at once a figure which takes into consideration the factors which tend to unbalance the current-transformer performance for a given application.

A wide variation in permissible loading has been shown by the ratios of calculated flux densities of 3.14/1 for figure 8, and 10.2/1 for figure 11. In general, it was found that a higher ratio was permissible when the maximum calculated flux density for either transformer did not greatly exceed the nominal saturation density of approximately 70,000 lines per square inch.

Conclusions

1. In the past, the application of high-speed (one-cycle) differential protection to generators has required the closest scrutiny of the current-transformer characteristics with respect to the duty imposed. This study involved particular attention to the effect of the d-c component of asymmetrical through faults. In all such cases, careful matching of current-transformer characteristics was required.

2. With the new relay, it suffices to look carefully only at the a-c characteristics of the transformers. The application is thus reduced to the simplicity of the older, slower-speed, induction-type relay, where a consideration of the a-c characteristics of the current transformers was generally sufficient.

3. A means of comparing the duty on the current transformers has been given through the method of calculating the theoretical maximum flux density required for the a-c component. When the resulting figure does not materially exceed the nominal saturation value of 70,000 lines per square inch, an allowable ratio between the values for the two current transformers of 3/1 provides ample safety factor to guarantee satisfactory relay operation.

Reference

1. Considerations in Applying Ratio Differential Relays for Bus Protection, Smith, Sonnemann, and Dodds. AIEE Transactions, volume 58, June 1939.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Frequency Modulation

W. L. EVERITT
FELLOW AIEE

RADIO communication makes use of a medium common to the whole world for the transmission of many signals simultaneously. In order to accomplish this a high-frequency electromagnetic wave has one of its characteristics varied in accordance with the instantaneous variations of the signal to be transmitted. The control of these variations is called modulation. The various simultaneous messages can then be separated by:

(*a*). Differences in the frequency band used.

(*b*). Differences in signal strength.

(*c*). Differences in direction of the source.

The allocation of frequencies and geographic location to stations engaged in different services is now a matter of legislation and international agreement. This regulation is necessary in order to reduce interference to a minimum.

The range of a radio station is limited solely by the point at which undesired interference reduces the quality of the received signal below a certain minimum. The amount of interference which may be tolerated differs with different classes of service, for instance, it would be less on a broadcast program designed to produce pleasure, than on a communication service designed to convey intelligence.

There are five principal sources of interference to radio reception. They are:

(*a*). Interference from other radio stations.

(*b*). Interference from natural electrical disturbances such as thunderstorms (static).

(*c*). Interference from electrical equipment not intended for radio purposes.

(*d*). Interference between identical signals traveling from the station originating the desired signal, but over two different paths. Since radio waves are alternating phenomena resolvable into a band of frequencies, the addition of two similar signals traveling over different paths must take account of both magnitude and phase. Distortion in the resultant signal may result due to the varying phase relations between the components with the same frequency in the two signals. One of the paths is usually caused by reflection from some medium such as the ionosphere. If this path varies in length with time, fading will result. When this produces distortion the phenomenon is called selective fading.

(*e*). Interference from random noise produced in the receiver by fluctuations in the motion of the electrons in the early stages of the amplifiers.

The major problems of the radio engineer are:

I. To obtain the maximum range at the minimum cost.

II. To secure the desired quality in the reproduction of signals.

Because the range is determined by the interference, and the quality is greatly affected by it, the reduction of interference becomes of paramount importance.

The reduction of interference must be accomplished by making use of some characteristic which differentiates the desired signal to a greater or less extent from the undesired interference. Four methods of differentiation have been extensively used. Each method in turn has its limitations. These methods and their limitations are:

1. Use of high power in the transmitter so that the strength of the desired signal will dominate the undesired.

This method is limited by the cost of high powered transmitters and by the interference it introduces to other services. Furthermore it does not affect selective fading since both signals (coming over two paths) are increased by the same amount.

2. Increasing the modulation of the radio wave to the greatest possible value.

This method is limited in amplitude modulation because it is not possible to vary the magnitude of a radio wave by more than 100 per cent and interfering signals, including static, will in general be modulated by similar amounts.

3. Use of selective circuits in the receiver so that only energy in the narrow band of frequencies which includes the desired signal will be received.

This method is limited because a definite band width is necessary for any given quality of reproduction and within this band there may be some portion of the energy in the spectrum of the interference.

4. Use of directive antennas at the receiver so that it is most sensitive to electromagnetic waves coming from the direction of the transmitter creating the desired signal and is insensitive to radiations originating in other directions.

This method is limited by the expense of directional antennas and by the fact that some interference may be originating in the same direction as the desired signal.

It is apparent that the methods just mentioned, taken individually or in combination, do not offer a complete solution of the problem. In fact no complete solution would appear possible, as the ultimate range of any transmission must be determined by the tolerable interference. However, any method which offers increased possibilities in the differentiation between desired signal and interference may be used to improve transmission. *Frequency modulation* offers such an additional method by which interference may be separated from the desired signal and it is the purpose of this paper to outline the principles and practices by which this may be accomplished.

The use and study of frequency modulation is not new. The Poulsen arc, developed before 1914, transmitted continuous-wave telegraph signals in which the frequency was shifted from one value to another when the key was depressed. Carson[1] and Roder[2] made theoretical investigations of the effects of frequency modulation on the spectrum of the modulated wave. Carson's investigation was

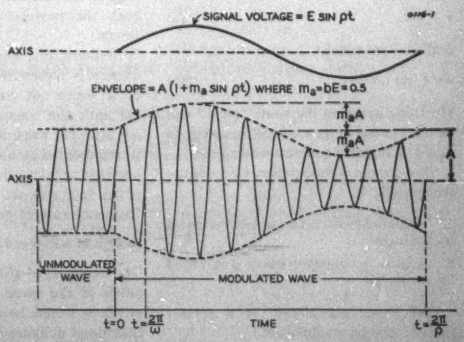


Figure 1. An amplitude - modulated wave

Paper 40-116, recommended by the AIEE committee on communication, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted April 23, 1940; made available for preprinting May 27, 1940.

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1. For all numbered references, see list at end of paper.

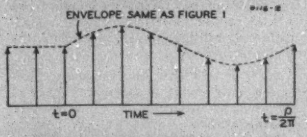


Figure 2. Vector diagrams of the amplitude-modulated wave of figure 1 for successive instants

made to analyze the proposal that frequency modulation could be used to reduce the band width required for a given signal. He proved that, on the contrary, frequency modulation never reduced the band width and might greatly increase it. Mathematics provides a correct answer to questions which are asked by its means, but it cannot be expected to provide answers to questions which are not asked. What was overlooked in the early mathematical analyses was the fact, later demonstrated by Armstrong,[3] and subsequently by Carson[4] and Fry, that frequency modulation provides an important method of distinguishing between desired and undesired signals which occupy the same portion of the frequency spectrum.

It will be necessary to go into some details of the principles of frequency modulation in order to show the reasons for this effect.

Modulation

Modulation of a radio wave is the process by which some characteristic of the radio wave is varied in accordance with the time variation of a signal, such as the instantaneous variations associated with speech, music, or the manipulation of a telegraph key. A general alternating wave may be represented by the equation

$$e = A \sin \theta \tag{1}$$

where θ is given by the relation

$$\theta = \omega t + \phi \tag{1a}$$

and so

$$e = A \sin (\omega t + \phi) \tag{1b}$$

(In this discussion the word "wave" will be used in one of its accepted meanings to denote a repetitive phenomenon.)

Two groups of modulation methods are recognized.

1. Amplitude modulation where A is varied by the signal.
2. Angular modulation where ϕ is varied by the signal.

(Frequency modulation is a special form of angular modulation.)

Amplitude Modulation

In an amplitude-modulated wave the amplitude is varied about its mean value in proportion to the signal. Let the original signal (such as the sound pressure on the microphone) be represented by the function $f(t)$. Then the amplitude factor A of equation 1b is modified by $f(t)$ to give the amplitude-modulated wave

$$e = A[1 + bf(t)] \sin (\omega t + \phi) \tag{2}$$

where b is a factor determined by the design and operation of the modulating system and has dimensions such that $[bf(t)]$ is a pure numeric. b is usually a constant, but in some cases it is made a function of audio frequency. For example, if it is made to change with frequency in the proper manner compensation may be secured for defects in the frequency characteristic of some other part of the system.

The amplitude variation cannot carry the amplitude below zero. Therefore the factor b should be so chosen by the operator that $[1 + bf(t)]$ never becomes negative. Therefore $[bf(t)]$ should not exceed an absolute value of unity. This absolute value of the maximum of $[bf(t)]$ is called the amplitude *modulation factor* and is given the notation m_a.

If the signal $f(t)$ is sinusoidal with a frequency $\rho/2\pi$, equation 2 becomes

$$e = A(1 + m_a \sin \rho t) \sin \omega t \tag{3}$$

The curve of equation 3 is illustrated in figure 1 for $m = 0.5$ and $\omega/\rho = 10$. It will be noted that the wave crosses the axis at regular time intervals of $2\pi/\omega$ seconds for both the modulated and unmodulated waves.

In alternating phenomena a single frequency is represented by the projection of a vector of constant length rotating with the constant angular velocity $\omega = 2\pi f$. The wave of equation 2 could also be represented by a vector rotating with a constant angular velocity ω, but the length of the vector would be changing at a low frequency rate as given by the equation

$$\text{Length of vector} = A[1 + bf(t)] \tag{4}$$

The term $A[1 + bf(t)]$ is called the *envelope* of the wave. In equation 3 the envelope would be $A[1 + m_a \sin \rho t]$ as is illustrated in figure 1.

In drawing vectors which represent alternating phenomena it is common practice to consider that the observer is traveling on a platform which is also rotating about the same center with a velocity ω. The original vector would then appear to be stationary and could be represented by a single drawing. However, if either the magnitude or the phase of the vector is changing with time, a series of successive drawings is necessary to illustrate what is happening.

These successive drawings of stationary vectors for the wave of figure 1 are shown in figure 2 for time intervals of one-eighth

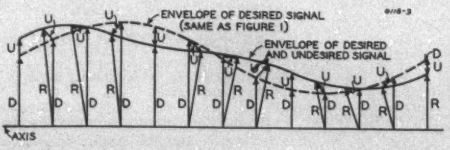


Figure 3. Interference with an amplitude - modulated wave of a carrier of slightly different frequency

D—Vector of desired signal
U—Vector of undesired or interfering signal
R—Resultant vector $(D+U)$ of sum of desired and undesired signals

the period of the low-frequency wave producing the modulation.

At the receiver the detector produces a response which is proportional to the envelope of the modulated wave (except for the constant component).

Interference of Two Amplitude-Modulated Waves

If a second amplitude-modulated wave of the same carrier frequency and phase is added to the wave of figure 1 the resultant wave will have an envelope which is the sum of the envelopes of the two waves, for the vectors will be adding in phase. The interfering effect will be noticeable if the undesired signal is as much as one per cent of the desired signal. Hence it is desirable to make the value of m_a as large as possible, since the operator of a given communication system cannot control the modulation of the interfering wave with the undesired signal.

If the frequency of the interfering wave is slightly different from the desired wave (the difference being too small to eliminate it by selective circuits) then the interfering wave will produce a variation in the envelope which variation has an amplitude equal to the magnitude of the interfering wave (even if it is unmodulated). This additional variation will occur at a frequency which is equal to the difference

between the carrier frequencies of the desired and undesired signals, and will produce a squeal which is further superimposed on the resultant envelope. This is illustrated by the vector diagrams in figure 3, where the undesired signal has a frequency which exceeds the frequency of the desired signal by $1.5\rho/2\pi$. It is seen that the resultant envelope is modified by an additional component equal to the magnitude of the undesired wave, and so introduces interference proportional to the magnitude of the interfering wave.

Again it is apparent that the amplitude of the envelope of the desired signal should be kept as large as possible in order that the interference may be minimized. If equation 2 represents current or voltage, the amplitude of the envelope may be increased by increasing either the power or the amount of modulation (m_a).

Angular Modulation

In angular modulation (of which frequency modulation is a subdivision) the angle ϕ of equation 1*b* is given by a function of time which is related, but not in all cases, directly proportional, to the signal function $f(t)$. The two principal subdivisions of angular modulation which

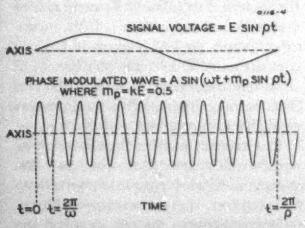


Figure 4. An angular-modulated wave

The 1st, 4th, 7th, 10th, and 13th cycles are shown in detail in figure 5

have been extensively studied are phase modulation and frequency modulation.

(*a*). Phase Modulation

In this type of modulation the phase angle ϕ is made to vary in accordance with the signal. That is

$$\phi = b_1 f(t) \tag{5}$$

where b_1 is a *constant* determined by the design and operation of the modulating system. When equation 5 is inserted in equation 1*b* the wave becomes

$$e = A \sin [\omega t + b_1 f(t)] \tag{6}$$

The maximum value of $b_1 f(t)$ is called the *phase modulation factor* m_p. It is the maximum number of radians by which the phase of the carrier is altered during modulation. If the signal is sinusoidal with a frequency $\rho/2\pi$, equation 6 becomes

$$e = A \sin [\omega t + m_p \sin \rho t] \tag{7}$$

(*b*). Frequency Modulation

In this type of modulation the *instantaneous frequency* is varied about the average value $\omega/2\pi$ in proportion to the instantaneous value of the signal. By definition, the use of the word "frequency" is extended to the general equations 1 and 1*b* by the relation

$$2\pi f_{inst} = \frac{d\theta}{dt} = \omega + \frac{d\phi}{dt} \tag{8}$$

Since ω is a constant (2π times the carrier frequency) the signal must modify $d\phi/dt$ so that the instantaneous frequency is given by the relation

$$f_{inst} = \frac{\omega}{2\pi} + b_2 f(t) \tag{9}$$

where b_2 is a design and operating constant. The maximum value of $b_2 f(t)$ is the maximum deviation in instantaneous frequency of the modulated wave from the unmodulated one and is called the *frequency modulation factor*, or frequency deviation, m_f. If $f(t)$ is a sine wave with a frequency $\rho/2\pi$ then

$$b_2 f(t) = m_f \sin \rho t \tag{10}$$

If equation 10 is combined with equations 8 and 9

$$2\pi f_{inst} = \omega + 2\pi m_f \sin \rho t = \omega + \frac{d\phi}{dt}$$

which gives

$$\phi = \int 2\pi m_f \sin \rho t dt = -\frac{m_f}{f_\rho} \cos \rho t$$

where f is the frequency of the modulating signal. If this phase angle is inserted in equation 1*b* the result will be

$$e = A \sin \left[\omega t - \frac{m_f}{f_\rho} \cos \rho t \right] \tag{11}$$

Equations 11 and 7, which apply to a signal with a single frequency, do not differ appreciably (except for a 90-degree shift in the modulation phase). In equation 11 the maximum shift in phase (corresponding to the phase modulation factor m_p) will be

$$m_p = \frac{m_f}{f_\rho} \tag{12}$$

where m_f is the frequency deviation and f_ρ the modulating audio frequency. The value of m_f when f_ρ is the maximum audio or signal frequency to be transmitted is called the *deviation ratio*.

m_p in phase modulation and m_f in frequency modulation are arbitrary design factors. Unlike amplitude modulation they are not restricted to a maximum value of unity, for m_p may be hundreds of radians or m_f thousands of cycles per second if desired. The limitations on m_p and m_f will be determined by the allowable frequency spectrum and will be discussed later.

The distinction between phase and frequency modulation is as follows: if the frequency, but not the intensity of the modulating signal changes

m_p is constant in phase modulation.

m_f is constant in frequency modulation.

It follows from equation 12 that in frequency modulation the phase deviation m_p is inversely proportional to the modulating frequency. On the other hand in phase modulation the frequency deviation is directly proportional to the modulating frequency.

Figure 4 is an illustration of the angular modulation as represented by equation 7 for the case where $m_p = 0.5$ and $\omega/\rho = 12$. On a casual examination this would appear to be a single frequency wave. However, the intervals at which it crosses the axis vary throughout the audio cycle. In order to show this the 1st, 4th, 7th, 10th, and 13th cycles are expanded and shown in figure 5. It is seen that the varying shift in phase also produces a change in frequency which varies throughout the low-frequency cycle.

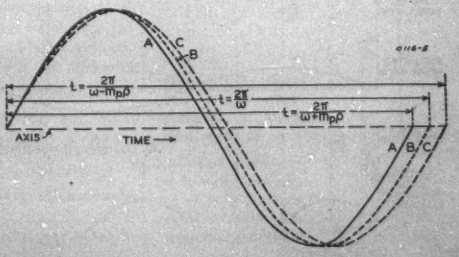


Figure 5. Expansion of individual cycles in figure 4

A—1st and 13th cycles of figure 4

B—4th and 10th cycles of figure 4

C—7th cycle of figure 4

The successive vector diagrams for the angular-modulated wave of figure 4 (corresponding to the diagrams of figure 2 for an amplitude-modulated wave) are shown in figure 6. The signal wave is included for identification of the various instants.

The difference between phase and frequency modulation may be illustrated by the way the motion of the resultant vector would appear to an observer riding with the carrier vector. In phase modulation, two audio signals of equal amplitude, but of different frequencies, would produce equal angular *amplitudes* in the apparent swing of the resultant vector. In frequency modulation two audio signals of

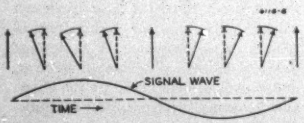


Figure 6. Vector diagrams of the angular-modulated wave of figure 4 for successive instants

Solid-line vectors are vectors of modulated wave

Dashed-line vectors are vectors of unmodulated wave

equal amplitude would produce equal maximum angular *velocities* in the apparent swing of the resultant vector. In this latter case (frequency modulation) the maximum angle of swing would be inversely proportional to the audio frequency (as is indicated by equation 12). This is illustrated by figure 7 where the vectors for both frequency and phase modulation are drawn for two signals with an audio-frequency ratio of two to one. Note that in phase modulation the maximum angle ϕ_m is the same for both signals while for frequency modulation the maximum angle ϕ_m for signal A (the lower frequency) is twice that for signal B. Since the angular *velocity* is proportional to the instantaneous value of the signal in frequency modulation the vector reaches its maximum angle of deviation when the signal is zero while in phase modulation it reaches its maximum angle of deviation when the signal is a maximum.

Other Types of Angular Modulation

Phase and frequency modulation are not the only possible types of angular modulation, but are only two members of an infinite group. Other possible types are:

(*c*). Angular Acceleration Modulation

In this type of modulation the second time derivative of ϕ is directly proportional to the signal function

$$\frac{d^2\phi}{dt^2} = b_2 f(t)$$

In this type m_p would be inversely proportional to the square of the audio frequency.

(*d*). nth Order Modulation

In this general type of angular modulation the nth derivative of ϕ is directly proportional to the signal function.

$$\frac{d^n\phi}{dt^n} = b_{n+1} f(t) \qquad (13)$$

In this type m_p would be inversely proportional to the nth power of the frequency for modulating signals of equal intensity.

In radio transmission by angular modulation means are provided at the receiver so that the detected signal is proportional to the angular modulation (of the particular subdivision selected) and at the same time this detected signal is made unresponsive to amplitude variations.

Note: ϕ_m is same for both signals for phase modulation. ϕ_m is inversely proportional to signal frequency for frequency modulation. Maximum velocities of vectors are same for both signals for frequency modulation

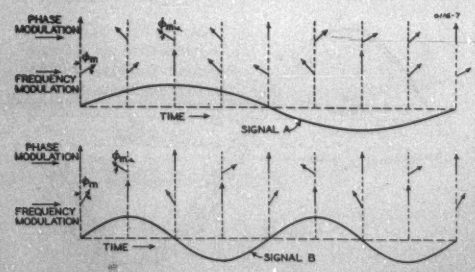


Figure 7. Comparison of phase and frequency modulation by means of vector diagrams

These means will be discussed in more detail later.

Interference of Two Angular-Modulated Waves

When two angular-modulated waves of the same carrier frequency are added together, the total angular modulation is not the sum of the two individual modulations. This is in distinct contrast to amplitude modulation where the resultant envelope is the sum of the individual envelopes.

This can be illustrated by figure 8 where an angular-modulated wave B is represented by a vector whose angle is changing with time. This is added to a larger vector A which for the moment will be assumed to be unmodulated. The resultant vector R will be the sum of the two vectors.

It is apparent that if B is less than A, then no matter what the total angular variation of B may be (even if it is hundreds of radians) the total angular variation between R and A cannot exceed $\tan^{-1}(B/A)$. For instance if $B/A = 0.5$ the maximum value of m_p for the vector R when A is unmodulated is $m_p = 0.46$. If $B/A = 0.5$ and A in turn has its angle modulated, then the difference between the angle of A and that of R cannot exceed 0.46 radian at any instant. If the modulation factor (m_p) of A is made large in comparison with 0.46, the interference of B becomes negligible, in spite of the fact that the magnitude of B is by no means negligible in comparison with A.

This analysis justifies the experimental results which show that when two frequency-modulated signals are picked up by a receiver, there is no appreciable interference between the two signals if the stronger exceeds the weaker by a ratio of two to one or more.

It will be seen that the greater the value of m_p used for the desired signal the greater is the discrimination against the undesired signal, but this discrimination is not affected by the value of m_p used in the undesired signal.

The discrimination against interference obtained by angular modulation applies to all five types of interference enumerated in the early part of the paper. In particular static may be represented as a vector of varying phase and magnitude. The selective circuits of the receiver admit only those components within the band to which it is receptive. If the amplitude of the admitted noise does not exceed half the amplitude of the desired wave, a very small amount of noise will be introduced into the output. The greater

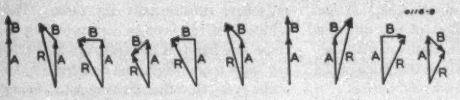


Figure 8. Vector diagrams showing interference in angular modulation

A is vector of desired signal—unmodulated
B is vector of interfering signal (same carrier)
R is vector of total wave (*A*+*B*)

the average phase deviation in comparison with the angle 0.46 (approximately 0.5) the greater will be the discrimination against the noise. It should also be observed that components of the noise vector which differ in frequency from the carrier by superaudible frequencies, will produce superimposed angular velocities above audibility and so do not contribute to the noise, as long as the noise is small compared with the signal.

In radio operation it will be found that if a portable receiver is driven in an automobile away from a frequency-modulated transmitting station, no appreciable noise will be experienced until the desired field strength drops to twice the noise field strength (taking into account only those components of noise accepted by the selective circuits of the receiver). The noise then rises rapidly, so that a sharp threshold is experienced.

Within the distance limited by the threshold, the signal-to-noise ratio can be improved by either increasing the power or increasing the modulation factor (either phase or frequency). Since power is proportional to the square of voltage or current in a given system, doubling the frequency deviation in frequency modulation has the same effect on the signal-to-noise ratio as increasing the transmitted power four times. In general an increase in the maximum frequency deviation by a ratio n would be equivalent in its effect on the signal-to-noise ratio to an increase in power by the ratio n^2.

The actual voltage produced by noise in the amplifier of a radio receiver increases with the width of the band accepted, the rate of increase depending on the type of noise. This introduces some disadvantage to the use of a wide band, because a stronger desired wave is necessary to insure that the desired voltage shall exceed the noise voltage.

R. F. Guy of the National Broadcasting Company reported before the Federal Communications Commission that in experiments with a one-kw transmitter and an antenna 1,000 feet high, the threshold for a value of m_f equal to 75 kilocycles was at 86 miles, while with an m_f of 15 kilocycles the threshold was at 100 miles due to the smaller noise voltage accepted by a more selective receiver. Within the threshold distances, however, there is a greater discrimination against noise with the greater frequency deviation.

The second major objection to the use of a large frequency deviation is that it would limit the number of stations which can serve a given area if a fixed total band width is allowed for the service.

A compromise must be reached and standard set before the use of frequency modulation is generally adopted so that the receivers may work with the transmitters. In order to study the possible or required allotment, a spectrum analysis must be made of the different classes of modulation.

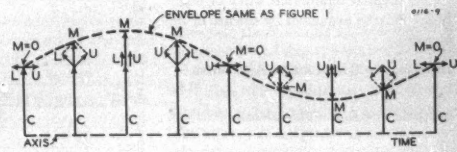


Figure 9. Vector diagram of carrier and side frequencies in an amplitude-modulated wave

C—Carrier vector (constant length)
U—Upper-side-frequency vector
L—Lower-side-frequency vector
M—Modulation vector (sum of *U* and *L*)
Vector of complete wave is sum of *C* and *M*

Spectrum Analysis of Amplitude Modulation

The wave of equation 2 may be expanded by the use of simple trigonometric identities. This equation becomes

$$e = A \sin \omega t + \frac{mA}{2} \cos (\omega - \rho)t - \frac{mA}{2} \cos (\omega + \rho)t \quad (14)$$

Equation 14 shows that the wave which is amplitude modulated by a single frequency may be analyzed into three component frequencies with the following designations:

$A \sin \omega t$	The carrier
$\frac{mA}{2} \cos (\omega - \rho)t$	The lower side frequency
$\frac{mA}{2} \cos (\omega + \rho)t$	The upper side frequency

The three components may be represented by three vectors rotating at different angular velocities. Again if the observer were rotating with the carrier vector, this vector would appear to be stationary. The upper side-frequency vector would appear to be rotating *counter-clockwise* at a velocity ρ and the lower side frequency would appear to be rotating *clockwise* at the same velocity ρ.

The three vectors corresponding to the wave of figure 1 are shown in figure 9. It will be observed that the upper and lower side-band vectors add together to form a vector M called the modulation vector, which is always in phase with the carrier vector, but which varies in magnitude.

The three component frequencies of equation 6 are represented graphically in figure 10. This is shown primarily so that it may be compared later with the frequency spectrum used in frequency modulation.

If the original signal were a complicated sound wave instead of a single frequency, a spectrum analysis would show it to be represented by a band of frequencies. The lower and upper side frequencies would expand into two bands of frequencies each as wide as the band of the original audio signal. For instance if the signal were restricted to a band of 0–5,000 cycles the two side bands would extend from 5,000 cycles below to 5,000 cycles above the carrier frequency. Since the quality of a signal depends upon the width of the band which may be transmitted, an improvement in the quality of transmission would require an extension of the frequency spectrum occupied by the radio

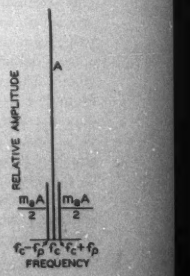


Figure 10. Spectrum analysis of an amplitude - modulated wave

f_c—Carrier frequency
f_p—Audio frequency
A—Carrier amplitude
m_a—Modulation factor = 0.5 in this case

wave. However, the narrower the frequency band which is used the greater will be the number of stations which can be accommodated. In practice a compromise must be made. Standard broadcasting stations in North America are assigned carrier frequencies in the range of 550 to 1,600 kilocycles, these assignments being separated at intervals of 10 kilocycles. In order to prevent interference, selective circuits are required in the receiver which are so sharp in most commercial models that side-band components more than 3,000 cycles away from the carrier are greatly attenuated. Hence the quality which is permissible in practical operation is limited by the major problem of interference.

Spectrum Analysis of Angular Modulation

The angular-modulated wave of equation 7 may be expanded by the use of the identities

$$\sin(p\sin x) = 2[J_1(p)\sin x + J_3(p)\sin 3x + J_5(p)\sin 5x + \dots] \quad (15a)$$

$$\cos(p\sin x) = J_0(p) + 2[J_2(p)\cos 2x + J_4(p)\times \cos 4x + J_6(p)\cos 6x + \dots] \quad (15b)$$

where $J_n(p)$ is the nth order Bessel function of the first kind. Equation 7 may be written

$$e = A[\sin\omega t\cos(m_p\sin\rho t) + \cos\omega t\times \sin(m_p\sin\rho t)] \quad (16)$$

If equations 15a and 15b are inserted in equation 16 the following result will be obtained

$$\begin{aligned} e = A\{&J_0(m_p)\sin\omega t + \\ &J_1(m_p)[\sin(\omega+\rho)t - \sin(\omega-\rho)t] + \\ &J_2(m_p)[\sin(\omega+2\rho)t + \sin(\omega-2\rho)t] + \\ &J_3(m_p)[\sin(\omega+3\rho)t - \sin(\omega-3\rho)t] + \\ &J_4(m_p)[\sin(\omega+4\rho)t + \sin(\omega-4\rho)t] + \\ &\dots\dots\dots\dots\dots\dots\dots\dots + \\ &J_n(m_p)[\sin(\omega+n\rho)t + \\ &(-1)^n\sin(\omega-n\rho)t]\} + \\ &\dots\dots\dots\dots\dots\dots\dots\dots \end{aligned} \quad (17)$$

This indicates that there are an infinite number of side frequencies for a single-frequency signal. However this is not as bad as might at first appear because for any given value of m_p, there will be a value of n above which the coefficients $J_n(m_p)$ fall off rapidly and become negligible. This is shown in figure 11. For example if m_p is one-half radian or less, only the first pair of side frequencies is important. On the other hand if m_p is equal to 20 radians, side frequencies out to the 24th pair would be appreciable. For large values of n this rapid falling off of $J_n(m_p)$ occurs just beyond $n = m_p$. Observe also that the value of the carrier component is always reduced when modulation occurs since $J_0(m_p)$ is less than one for all values of m_p different from zero. This is in contrast with amplitude modulation where the value of the carrier is not affected by modulation.

Figure 4 was drawn for a phase-modulation factor of 0.5 and so the first pair of side bands are the only ones of importance. If all other side bands are neglected the vector diagrams including the side

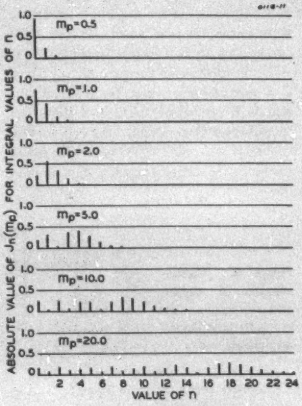


Figure 11. Values of the Bessel function of the first kind for integral orders

bands for different instants of figure 4 can be shown as in figure 12. The signal wave is shown for identification. The carrier and resultant vectors are the same as those shown in figure 6. The modulation vector, which is the sum of the two side-band vectors, is always 90 degrees out of phase with the carrier and varies in magnitude in the same way that the modulation vector varies in amplitude modulation. The neglect of higher-order side frequencies is the same as an assumption that there is a negligible difference between the arc and a tangent line of the same length when the angle is small.

When the modulation vector is added to the carrier vector it causes the resultant vector alternately to advance beyond and retard behind the carrier vector. The maximum advance and retardation is approximately one-half radian. The length of the resultant vector is substantially constant. If the additional side bands were included the length of R would be exactly constant.

If the phase modulation exceeds one-half a radian additional side bands must be included because the arc and chord are no longer substantially the same. The addition of the vectors corresponding to these side bands is illustrated in figure 13 for $m_p = 1$ and for one-quarter of an audio cycle, the other three-quarters being similar. It will be noticed that each pair of side bands has associated with it a modulation vector which maintains a constant phase with respect to carrier (assuming that phase reversals are taken care of by negative signs).

If the modulated wave represents a quantity whose square is proportional to power in a given system the *average* power in an angular-modulated wave is not changed by the modulation, as the rms value of the wave is not modified if the amplitude remains constant. Therefore the square root of the sum of the squares of the carrier and all the side-band components remains constant for all values of m_p. The side-band power is obtained by a reduction in carrier power. This is also proved by the well-known relation

$$J_0^2(m_p) + 2\sum_{n=1}^{n=\infty} J_n^2(m_p) = 1$$

for all values of m_p. The number of terms which are of importance in the infinite series can be evaluated by setting

$$J_0^2(x) + 2\sum_{n=1}^{n=s} J_n^2(m_p) \geq \lambda$$

Then if λ is taken as some value less than unity, the sum can terminate with a finite value of n equal to s. If λ is equal to 0.999 then 99.9 per cent of the energy in the wave would be due to side-band components corresponding to values of n equal to or less than s.

For example, if $m_p = 4$ and six components are taken in each side band

$$\begin{aligned} J_0^2(m_p) + 2\sum_{n=1}^{n=6} J_n^2(m_p) &= 0.157688 + \\ &2(0.004356 + 0.132569 + 0.185072 + \\ &0.079017 + 0.017450 + 0.002411) \\ &= 0.999438 \end{aligned}$$

and all the components corresponding to $n > 6$ would contain only 0.0562 per cent of the energy.

The constancy of power output is in marked contrast to amplitude modulation where the carrier power remains constant and the side-band power is added. For that reason certain problems in design are simplified in a phase- or frequency-modulated transmitter. This will be discussed in the section on transmitters.

Comparison of the Spectra of Phase and Frequency Modulation

In phase modulation the value of m_p is made directly proportional to the maxi-

Table I

Audio Frequency	m_p for 60,000-Cycle Deviation	Approximate Number of Side-Band Components Required	Approximate Band Width in Kilocycles
30	2,000	4,030	120.06
60	1,000	2,020	120.20
300	100	208	124.8
2,500	24	46	140
3,000	20	24	144
5,000	12	30	150
10,000	6	16	160
15,000	4	12	180

mum value of the signal. If two different audio frequencies have equal amplitudes, and modulate the signal in succession, the same number of side-band components would be necessary for each case and these components would have the same relative magnitude. It has been shown that the advantage of angular modulation in the reduction of interference requires the use of large values of m_p for the desired signal. If the value of m_p for a special case is taken equal to 20, then by figure 11 it is apparent that approximately 24 side-band components would be desirable for the upper side band and a similar number for the lower side band. Therefore if an audio signal of high quality containing components up to 15,000 cycles were to be transmitted, a band width of approximately $2\times24\times15{,}000$ or 720,000 cycles would be required. This is obviously impracticable. For this reason phase modulation (as distinguished from frequency modulation) has not been used for radio transmission.

In frequency modulation the value of m_f is made directly proportional to the maximum value of the signal. If two different audio frequencies have equal amplitudes and modulate the signal in succession with equal values of m_f, by equation 12 the values of m_p for the two cases will be inversely proportional to the audio frequency. Thus if m_p is equal to 4 for 15,000 cycles it would be equal to 40 for 1,500 cycles and equal to 400 for 150 cycles. A study of figure 11 shows that the number of components of appreciable magnitude in each side band is slightly in excess of m_p. Therefore as the modulating frequency is reduced, the number of components necessary increases, and the modulated wave occupies almost a constant band width in the spectrum. As an example consider a case where the maximum frequency deviation is assumed to be 60,000 cycles. Then if a high quality signal is to be transmitted, frequency components in this signal up to 15,000 cycles might be desired. If the wave were frequency modulated with a 60,000 cycle deviation ($m_f=60{,}000$) at 15,000 cycles m_p would equal $60{,}000/15{,}000=4$ radians. For this case figure 11 shows that approximately six components in each side band separated at intervals of 15,000 cycles are desirable and the corresponding band width would be $2\times6\times15{,}000$ or 180,000 cycles. On the other hand if the wave were to be frequency modulated with a 60,000 cycle deviation by a 3,000 cycle wave $m_p=60{,}000/3{,}000=20$ and approximately 24 components in each side band separated at intervals of 3,000 cycles would be desirable. The band width for this signal would be $2\times24\times3{,}000=144{,}000$ cycles which is somewhat less than that needed for $m_p=4$ at 15,000 cycles. Table I is constructed for a maximum deviation of 60,000 cycles.

The spectrum analysis for a deviation of 60 kilocycles and modulating frequencies of 2,500, 5,000, 10,000, and 15,000 cycles is shown in figure 14 and it is apparent that the signal is contained within a band width of approximately 200 kilocycles in all cases. In practice, no audio signal would contain only the higher audio frequencies and so it is found practicable to use a deviation of m_f of 75,000 cycles for a band width of 200 kilocycles.

The spectrum analyses for a modulating frequency of 15,000 cycles and deviation frequencies of 30, 15, 7.5, and 3.0 kilocycles are shown in figure 15.

It is apparent from figures 14 and 15 that when the deviation frequency is large compared with the audio frequency, the band width required is approximately twice the deviation frequency while when the audio frequency is large compared with the deviation frequency the band width is twice the audio frequency. The latter case coincides with the situation in amplitude modulation. In other words the band width required is approximately twice the larger of the two frequencies (audio or deviation). If the audio and deviation frequencies are approximately equal the band width required is approximately four times that of the larger frequency. (See figure 15 for $m_p=0.5$, 1, and 2.)

The spectra of figures 14 and 15 may be used for any other combinations of audio and deviation frequencies which have the same deviation ratio m_p by modifying the scale of abscissa so that the interval between adjacent components is equal to the audio frequency.

The reader must be cautioned that if a signal contains two or more audio frequencies, the resultant spectra cannot be obtained by adding the spectra resulting from each audio frequency alone (as can be done in amplitude modulation). However, the total spectra will remain approximately within the limits set by the maximum frequency deviation when the latter is large.

Although the discrimination against noise is proportional to m_p, it is impracticable to use large values of m_p at all audio frequencies because of the band width involved. However, noise and interference is the composite result of a larger number of noise components. If frequency modulation is employed, the maximum value of m_p is obtained for each audio component in the signal which will at the same time keep the side-band components within the limits in the spectrum assigned to the transmission. Therefore frequency modulation is the type of angular modulation which reduces the composite noise effect to the greatest practicable extent.

If the maximum modulation factor m_p (deviation ratio) is low, m_p less than 0.5, frequency modulation does not appear to have any advantages over amplitude modulation. The early proposals for the use of frequency modulation envisioned this method of operation and so were dis-

C—Carrier vector
U—Upper-side-frequency vector
L—Lower-side-frequency vector
} First pair only
M—Modulation vector (U+L)
R—Resultant vector (C+M)

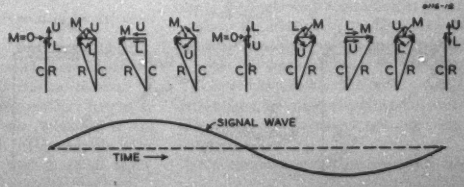


Figure 12. Vector diagram of carrier and side frequencies in an angular-modulated wave for low values of modulation

carded after the analyses of Carson[1] and Roder.[2]

Practical Considerations in Frequency Modulation

It has been shown that the reduction of interference makes frequency-modulated transmitters most desirable for the transmission of high-quality signals. However these transmitters require relatively large frequency bands. Therefore frequency modulation, or F-M, does not appear to be feasible in the present broadcast band. For high-quality broadcasting they should be allocated to high frequencies where band widths of 200 kilocycles are available. The Federal Communications Commission has assigned the frequencies from 42 to 50 megacycles for this service or a total of 40 channels. This is in the range of the so-called ultrahigh frequencies.

Radio waves with frequencies of the order of 40 megacycles and above are not reflected from the ionosphere, and so their range is limited by the curvature of the earth. For the same reason static is greatly reduced at these frequencies because the energy which lies in the ultrahigh-frequency spectrum and which is originated by electrical disturbances at distant points on the earth's surface cannot travel to the receiver over long distances. Other factors also reduce static at high frequencies. As an average, the static voltage producing interference in a receiver with a given band width and tuned to 40 megacycles is about $1/40$ of the static voltage which would be picked up by a receiver of the same band width tuned to 1,000 kilocycles. It is also possible to transmit a wide-band audio signal which requires corresponding wide side bands at ultrahigh frequencies because for practical reasons it is not desirable to assign carrier frequencies as close together as in the standard broadcast band and so sufficient band width is available for high-quality transmission. Therefore ultrahigh frequencies inherently offer an improvement in quality whether amplitude or frequency modulation is used.

However, there are three important difficulties with ultrahigh-frequency transmission for broadcasting purposes. The first difficulty is the effect of the curvature of the earth on ultrahigh frequencies. Because there is no reflection from the ionosphere, it is frequently stated that the limit of transmission for these frequencies is the distance from the transmitting antenna to the horizon. The equation for this distance is

$$d = 1.22\sqrt{H} \tag{18}$$

where

d is the distance to the horizon in miles
H is the height of the transmitting antenna in feet

For a height of 400 feet the distance to the horizon would be only 24.4 miles.

Within this distance the field strength of the signal is given approximately by the equation[6]

$$E = \frac{0.0105\sqrt{W}GHAF}{D^2} \tag{19}$$

where

E = field strength in microvolts per meter
W = power in watts
G = gain of the antenna over a half-wave dipole
A = receiver antenna height in feet
F = frequency in megacycles
D = distance in miles

The formula and the statement that the transmission is limited to the horizon are not strictly true because it is found that diffraction and refraction of the waves produce a signal[7] beyond the horizon, but this signal falls off more rapidly than the inverse-distance-squared term of equation 19.

The second difficulty with ultrahigh-frequency transmission is the noise produced locally by electrical apparatus. The principal sources of this noise are automobile ignition and fever therapy machines. These sources might be eliminated in time by legislation requiring adequate shielding.

A third difficulty with ultrahigh-frequency transmission is the sharp shadows thrown by buildings, hills, etc. Sharp shadows are produced in the field of any wave motion when the interfering bodies have dimensions large in comparison with the wave length, and so are particularly apparent at ultrahigh frequencies (short wave lengths).

Because of these difficulties the transmission of amplitude-modulated waves at ultrahigh frequencies has not made very much progress for broadcast transmission. However, these difficulties are only aspects of the fundamental problem pointed out at the beginning of the paper, that radio transmission is limited by the ratio of interference to signal. It has been shown that frequency modulation offers an important improvement in the solution of this problem. By its means the signal-to-noise ratio at any fixed distance may be increased. It seems probable an increase in transmission range may be secured by frequency modulation due to the greater signal-to-noise ratio and this may make economically feasible the use of ultrahigh frequencies for broadcasting purposes.

In field tests, adequate signals for the operation of an F-M receiver at two to three times the horizon distance are regularly reported when the transmitter is a high-powered one.

The wide band width which is required for frequency modulation is compensated

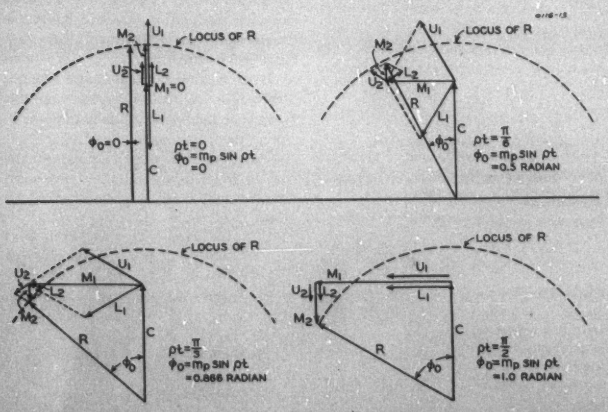
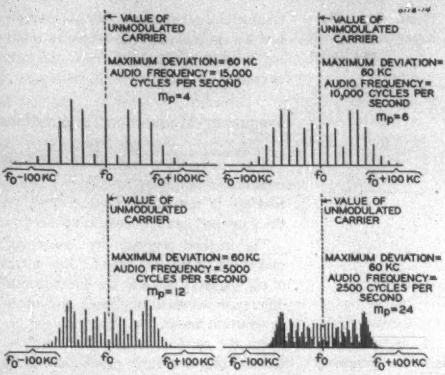


Figure 13. Vector diagram of carrier and two pairs of side frequencies in an angular-modulated wave where $m_p = 1$

U_1—First upper side band vector
L_1—First lower-side-band vector
M_1—First modulation vector (U_1+L_1)
U_2—Second upper-side-band vector
L_2—Second lower-side-band vector
M_2—Second modulation vector (U_1+L_2)
C—Carrier vector
R—Resultant vector



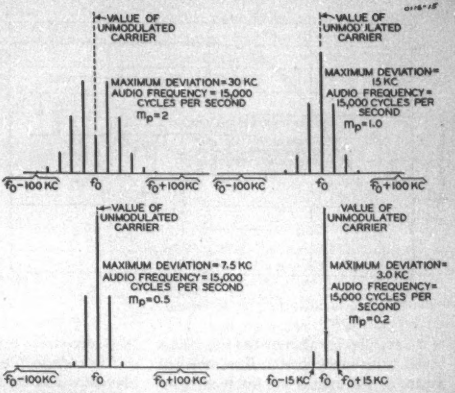


Figure 14 (left). Spectrum analysis of frequency modulation for a constant deviation and variable modulating frequencies

Figure 15. Spectrum analysis of frequency modulation for a constant modulation frequency and variable deviation frequency. (Signal is for phase modulation)

for by the reduction in interference between two stations on the same channel. In amplitude modulation, interference is caused if an undesired signal is one per cent of the desired signal. It has been shown that in F-M a ratio of two to one between desired and undesired signals is sufficient. If two stations of equal power and located in neighboring cities should operate on the same channel, there would be only a small territory about half way between the two stations where there would be any interference. Even in this territory, relatively simple directional antennas would be sufficient to pick out one station or the other. Therefore numerous stations could be located throughout the nation on the same carrier frequencies.

I. R. Weir, of the General Electric Company reported before the Federal Communications Commission that in their experiments they used a 150-watt transmitter at Albany and a 50-watt transmitter at Schenectady, a distance of 14.5 miles. They operated both transmitters on the same frequency with both frequency and amplitude modulation. In driving a car equipped with a receiver along a line between the two stations the following results were obtained:

Type of Modulation	Interference-Free Range of Albany Station	Transitional Distance With Interference	Interference-Free Range of Schenectady Station
Frequency	10.5	1.0	3.0
Amplitude	3.3	11.7	0.5

A further advantage of frequency modulation in the operation of the transmitter and receiver is that nonlinear distortion in frequency modulation is not affected by the nonlinearity of the tubes, as their nonlinearity is a function of amplitude. In F-M nonlinear distortion depends only on circuit design, that is, on nonlinear relations which are a function of frequency. For that reason it is claimed that high-quality reproduction is more practicable.

Frequency-Modulation Receivers

In the discussion of F-M receivers and transmitters, a certain familiarity with communication theory must be assumed in order to conserve space. The discussion will deal with present commercial practice.

Frequency-modulated receivers differ from amplitude-modulation receivers in three important respects. They are:

(*a*). The inclusion of a *limiter* to remove any amplitude modulation resulting from an interfering signal.

(*b*). The use of a special detector circuit called the discriminator to change the frequency modulation into a variable-amplitude signal.

(*c*). The use of a wide-band intermediate amplifier.

In addition it is much more important in a frequency-modulation receiver to have a high-gain intermediate-frequency amplifier, because the operation of the limiter is dependent upon a certain minimum signal being applied to its input. Also, if advantage is to be taken of the high-quality transmission which is possible with F-M, a better-than-average audio system and loud speaker should be included.

Except for these differences, the F-M receiver will follow the practice of amplitude-modulated receivers. The use of superheterodyne receivers is universal.

If a tuned-radio-frequency amplifier has impressed upon its grid a high-frequency voltage exceeding a certain minimum amplitude, the radio-frequency current in the tuned plate circuit will be practically independent of the magnitude of the input. This is because after the radio-frequency component of voltage in the plate circuit has reached an amplitude equal to the d-c component of the plate voltage no further increase in the radio-frequency component can be obtained for the instantaneous value of plate voltage cannot be driven negative. By the use of a high-gain tube and low values of plate voltage, saturation at relatively low values of grid excitation may be obtained. Figure 16 shows the circuit and the limiting action for a typical commercial F-M receiver. The operation of the limiter is the same as that of a class *C* amplifier[4] and the use of a bias obtained by a resistance in the grid circuit assists in securing a flat curve.

The use of a limiter is necessary because any amplitude modulation which reaches the detector will also produce amplitude variations in the reproduced signal. *The use of the limiter or its equivalent at the receiver is the most important component in an F-M system, for no reduction in interference will occur without its operation.* The limiter is possible in frequency modulation because the saturation does not affect the instantaneous frequency of the output.

The elimination of hum due to the use

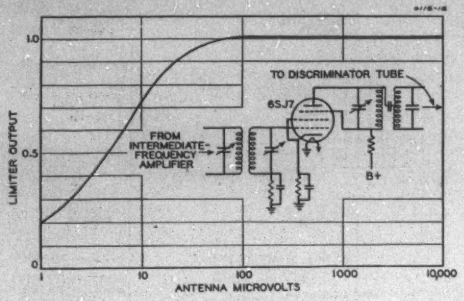


Figure 16. Characteristic and circuit of a limiter

of a-c supplies in receivers has also been a problem for many years. The principal source of this hum is amplitude modulation produced in the receiver by the hum component of the rectified d-c plate supply and by the heating of the cathodes by alternating current. If this occurs in the early stages of the receiver it is amplified along with the signal. While this hum level is reasonably well controlled in modern receivers, the limiter in a frequency-modulated receiver provides an additional improvement. This is particularly important because the elimination of other sources of interference makes the reduction of hum to an extremely low level much more desirable.

Because the audio amplifier and loudspeaker must reproduce the amplitude variations of the original signal, the discriminator or detector circuit must change the frequency variations into amplitude variations. The most common discriminator circuit in use is that of figure 17. The tuned transformer L_1-L_2 has a split secondary feeding two diode plates with the resistance loads R_1 and R_2. The voltage E_2 will be 90 degrees out of phase with the voltage across L_2 at the resonant frequency of L_2-C_2. The radio frequency across diode 1 in series with resistance R_1 is represented by the vector $E_a=E_1+E_2$ while that across diode 2 in series with resistance R_2 is $E_b=E_2+E_3$. When the output of the discriminator is at the intermediate frequency the phase relations will be those shown in diagram A. However, when the frequency shifts, the voltage across L_2, (E_1-E_2), shifts in phase. It can be shown that this voltage will follow the locus indicated by the circles. Hence E_a and E_b change in magnitude, one decreasing and the other increasing. By detector theory[5] the instantaneous value of the voltage across R_1 is proportional to E_a while that across R_2 is proportional to E_b. Therefore the instantaneous voltage E_4 supplied to the audio amplifier changes. Increases in frequency make E_4 positive and decreases make it negative.

The relation between the frequency deviation and the instantaneous value of E_4 is also shown in figure 17 for a typical receiver. The circuit constants must be selected so that the straight-line portion of the characteristic will accommodate the frequency shift which is used at the transmitter. The linearity of this characteristic affects the nonlinear distortion in the reproduced signal. It should be observed that its linearity is not a function of the tube characteristic. This makes it apparent that it is necessary to adopt standards at both receiver and transmitter which will be co-ordinated.

After a hearing before the Federal Communications Commission where all the problems were thoroughly discussed, the band width of 200 kilocycles per channel was adopted as standard. The allocation of channels adjacent to each other in the range of 42 to 50 megacycles simplifies the problem of receiver design, since no band-switching equipment will be required.

Because the intermediate amplifier must amplify a wider band of frequencies than is necessary in amplitude modulation a higher intermediate frequency is used. The present standard adopted is 4.3 megacycles for the intermediate carrier frequency.

A system which uses negative-frequency feedback in the receiver[4] has been proposed. It accomplishes similar results to those obtained by the use of the limiter, but as it is not at present available commercially, it will not be discussed here, although additional advantages are claimed for it.

Receivers are being manufactured which receive both amplitude and frequency modulation. In these combined receivers separate intermediate frequency transformers and detectors must be used. This makes the combination receiver somewhat more complicated, but complicated circuits have never been a bar to commercial production. This is exemplified by superheterodyne receivers retailing for $10 which have more extensive circuits than $200 sets of 15 years ago.

Frequency-Modulation Transmitters

Two important and quite different methods of obtaining frequency modulation are in use at the present time. A third method has also been announced.

The method proposed by Armstrong[3] makes use of the fact that for low values of m_p (m_p less than 0.5) the fundamental difference between amplitude and phase modulation lies in the phase relation between the carrier and side-band vectors. This is illustrated by a comparison of figures 9 and 12. Balanced modulators have been extensively used[6] in carrier-current systems to obtain the two side bands of amplitude modulation and eliminate the carrier. In the Armstrong system the carrier output of the oscillator is shifted 90 degrees and then used in a balanced modulator to obtain side-band components corresponding to amplitude modulation with this carrier phase. The output is then added back to a carrier component with the phase of the oscillator to form a phase modulation system. The maximum allowable modulation factor m_p produced with these components is 0.5 since only one pair of side frequencies is available.

A block diagram showing the Armstrong system is shown in figure 18. The

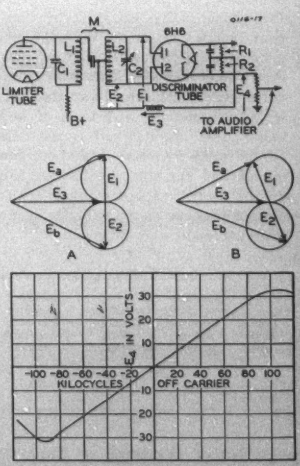


Figure 17. Characteristics and circuit of a frequency discriminator

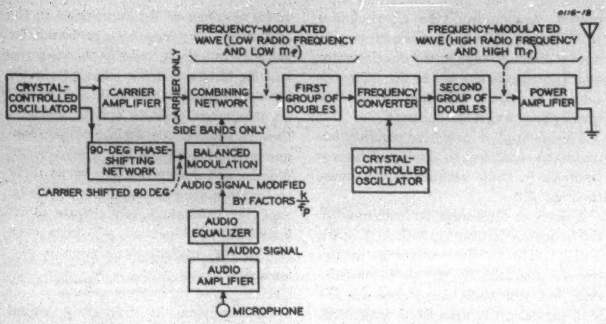


Figure 18. Block diagram of Armstrong frequency-modulated transmitter

several components required will be discussed in turn.

This method is fundamentally a phase-modulation system, but it may be converted into a frequency-modulation system if an audio equalizer is used before the modulation. The required characteristic of this equalizer is that the output voltage must be inversely proportional to the audio frequency of the input voltage. With this equalizer in the audio system the phase modulation will be inversely proportional to the audio frequency of the original signal. It has been shown that this is the requirement for frequency modulation and so the combination produces true frequency modulation.

It has been explained that with this system m_p is limited to a maximum value of 0.5, in the original modulation. On account of the characteristic of F-M which has been discussed, this maximum value of m_p can only be secured at the lowest audio frequency to be transmitted. The value of m_p at higher frequencies will be inversely proportional to the audio frequency. Then if a range from 40 to 15,000 cycles is to be transmitted the maximum value of m_p at 15,000 cycles will be $40/15{,}000 \times 0.5 = 0.0013$.

Such a method of obtaining frequency modulation, if used alone, would be entirely impractical since operation would be restricted to such low values of m_p and the advantages of frequency modulation lie in the use of large values.

If a radio-frequency amplifier has a large grid bias and relatively large radio-frequency voltage applied to its grid, the plate current will flow in pulses[8] containing harmonics of the grid exciting voltage. If the plate circuit is tuned to a harmonic of the grid voltage, the voltage across the tuned circuit will have a high value at this harmonic. For efficient operation this harmonic should be a low one, say the second or third. When tuned to a second harmonic the combination is called a frequency doubler.

It has been found that a frequency doubler also doubles the phase or frequency shift if an angular modulated wave is applied to the grid, and therefore doubles the value of m_p and also m_f for such a wave. A series of n doublers would multiply m_p by 2^n.

If the method of obtaining frequency modulation now being discussed is operated with a relatively low carrier frequency and the output is passed through a sequence of doublers or triplers, the value of m_p can be correspondingly increased. It has been shown that if a deviation of 75,000 cycles is desired, the value of m_p at an audio frequency of 15,000 cycles would be $75{,}000/15{,}000 = 5$. It has also been shown that for the wide audio range of 40–15,000 cycles the n_p which can be initially produced by the Armstrong method at an audio frequency of 15,000 cycles is 0.0013. Therefore the amount of multiplication of m_p required is approximately $5/.0013 = 3{,}750$. The number of doublers required is then obtained by the solution of the equation

$$2^n = 3{,}750$$

or

$$n = 12 \text{ nearly}$$

If a final carrier frequency of 41 megacycles is to be used and straight multiplication were to be employed, the carrier frequency at which the initial modulation should take place would be determined by the frequency multiplication required. In this case

$$\text{Initial carrier frequency} = \frac{\text{Final carrier frequency}}{\text{Multiplication of doublers}} = \frac{41{,}000{,}000}{2^{12}} = 10{,}000 \text{ cycles per second}$$

It is not possible to modulate a 10,000-cycle carrier by an audio frequency of 15,000 cycles, since the audio frequency must be less than the carrier frequency. Therefore some modification of the system must be made. The modification adopted is to perform the modulation at an initial carrier frequency of the order of 200 kilocycles and pass it through a first group of say six doublers. The carrier frequency has then been multiplied 2^6 times and has reached a value of 12.8 megacycles. If now a final carrier frequency of 41 megacycles is desired, the 12.8 megacycle signal is combined with the output of a second crystal oscillator whose frequency is selected so that a beat note of $41/2^6$ or 0.6406 megacycle is obtained. This does not affect m_p. The 640.6-kilocycle wave is then passed through a second group of six doublers to obtain the final 41-megacycle output. Since the initial frequency-modulated wave has now passed through 12 doublers, the multiplication of 2^{12} or 4,096 has been obtained.

The output of the second group of doublers is then amplified up to the final power required.

While this circuit seems complicated, it should be remembered that these operations can be performed at low power and with receiving-type tubes. The cost is not prohibitive for a transmitter station, since the investment in other equipment would be much greater.

The second method of frequency modulation operates in a distinctly different manner. If the capacity of a capacitor could be varied at an audio rate, and if this capacitor were included in the tuned circuit of an oscillator, it is apparent that the output would be frequency modulated.

The fundamental characteristic of a re-

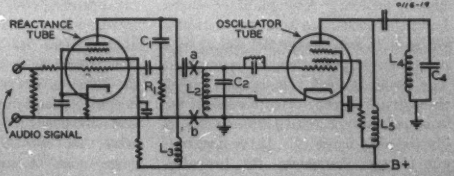


Figure 19. Circuit of an oscillator which is frequency-modulated by a reactance tube

actance is that the current flowing into the two terminals is 90 degrees out of phase with the voltage applied across these terminals. This same effect can be secured with a tube circuit. The method is illustrated in figure 19. The resistance R_1 is made small in comparison with the reactance of C_1. Then the alternating voltage between the control grid and cathode is substantially 90 degrees out of phase with the voltage impressed across the terminals a-b. But the plate current which flows in the tube is determined largely by the grid voltage. The choke L_4 provides a large impedance to alternating current so that the a-c component of the plate current will flow in the terminals a-b. The current which flows into the terminals a-b will be 90 degrees out of phase with the voltage across it because of the grid control and the circuit appears like a reactance at these terminals.

The magnitude of the reactance is a function of the amplification constant of the tube. In a variable-mu tube the amplification constant may be controlled by the voltage on the grid. Therefore if an audio voltage is also impressed on the control grid of the tube the effective reactance may be varied at an audio rate.

The terminals a-b are connected in parallel with the tuned circuit L_2-C_2 of a conventional oscillator whose output frequency is determined by the resonance of that circuit. With this combination a variation in the audio voltage on the grid of the reactance tube will produce a frequency-modulated wave in the output circuit of the oscillator L_4-C_4.

The circuit of figure 19 does not have the inherent stability of the system of figure 18 because the carrier frequency or frequency for zero modulation is not crystal controlled. Stability equivalent to crystal control is necessary in modern radio operation. In order to secure crystal control a more elaborate system is necessary. This is illustrated by the block diagram of figure 20.

The oscillator and reactance circuit are similar to those of figure 19. The oscillator usually operates at some submultiple of the desired frequency, say one-fourth or one-sixth. A frequency multiplier is used before the operation of the final power amplifier, as is standard practice at ultra-high frequencies. A sample of the output is brought back into a frequency converter where it is mixed with the output of a crystal oscillator for comparison purposes. The resultant beat note is then passed through a frequency discriminator of the same general type as used in receivers and illustrated in figure 17. If the final output changes frequency, the beat frequency passing into the discriminator will change. This change is used to produce a direct voltage in the discriminator which in turn is applied to the reactance tube to provide a correction on the frequency drift which has occurred.

This method of increasing stability has a marked similarity to the use of inverse feedback in audio amplifiers to increase their stability.

A delay or filter must be introduced in the frequency feedback circuit so that it is unresponsive to the variations in frequency produced by the audio modulation, but will make corrections for the long period drifts associated with oscillators which are not crystal controlled.

The two methods of frequency modulation transmitters each have their proponents. The Armstrong method is claimed to be more stable because the carrier frequency is directly controlled by the two crystals. The reactance tube method is simpler and would seem particularly applicable to low powers and portable equipment. It is too soon in terms of practical operation to be sure which will find the most general application.

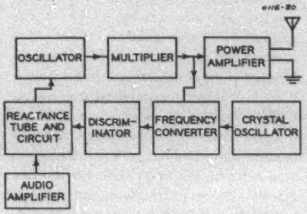


Figure 20. Block diagram of a reactance-tube-controlled frequency-modulated transmitter with crystal stabilization

The operation of the final amplifiers in both systems is essentially simpler than is the case in amplitude modulation, since attention need not be paid to the linearity of input-output amplitude curves.

In amplitude modulation the final high-power stage presents certain difficulties in operation. A transmitter normally requires[8] either a high-power audio amplifier with an output about 75 per cent of the rated carrier power to perform the modulation, or else the final stage must be operated at half its maximum efficiency. This is because in amplitude modulation the power output must be increased during modulation by an amount equal to the side-band power (50 per cent of the carrier power for $m=1.0$). The increase in power must be supplied by either an audio amplifier or by an increase in the efficiency of the output stage during the audio cycle. An increase in efficiency can only be obtained if the efficiency in the absence of modulation is limited to half its maximum possible value. Both of these expedients increase the cost of high-power stations materially. Since the amplitude and power output of an F-M transmitter are constant during modulation, the final stage can operate at its maximum efficiency at all times even though the original modulation is performed at a low power level where only receiving-type tubes are required.

The question is frequently raised whether the wide band which must be transmitted for F-M does not introduce difficulties in the tuned circuits. However, it should be remembered that the selectivity of any tuned circuits is given in terms of frequency ratio rather than absolute band width. A 200-kilocycle band width at 40 megacycles is only one-half of one per cent of the carrier frequency, while the 10-kilocycle band width used in standard broadcasting at 1,000 kilocycles is one per cent of the carrier frequency. Therefore no difficulties are introduced in the transmitter by the required absolute width of the band when the carrier frequency is high.

Application of Frequency Modulation to Services Other Than Broadcasting

Frequency modulation seems to have inherent advantages for other services than broadcasting. Important among these are its application to police and airway communication. The sharp limitation of the range obtained with F-M is an advantage and it would appear that many more police transmitters covering specific areas could be used without interference. In airway service some of the most important contacts are needed during severe electrical storms and F-M could make an important contribution in this field.

F-M would also appear to have advantages for military purposes where limited ranges are desired and interference is a particularly severe problem.

In police, airway, and military communication, high-quality reproduction is not necessary and so a more limited band would serve the purpose.

F-M has also been proposed for longer-distance communication by the use of relay or repeater stations spaced at intervals determined by the range of the transmitters. By the use of directional antennas this range can be increased. Previous proposals to use relay stations for

broadcast-station interconnection have not met with favor because of the limited range and additional interference which they would cause, but it appears that a large part of this objection is eliminated when F-M is used.

It is also possible to multiplex other services on F-M transmission, such as facsimile, transmitting this service along with a sound signal, but with a reduction in the signal-to-noise ratio. Another suggestion has been to transmit two sound signals to obtain binaural reproduction. The possibilities of these uses have been only partially explored.

Conclusion

It would appear that frequency modulation is capable of producing a marked change in broadcasting within the next few years. It is very doubtful if it will eliminate the use of the standard broadcast frequencies, as they are still capable of covering larger distances when (and only when) a transmitter is given exclusive use of a channel. It seems probable that many local stations designed to cover a limited area will be transferred to F-M operation, and the number of cleared channels increased so as to take better advantage of the limited band of standard broadcast frequencies available. The development in these lines must eventually respond to the laws of economics and engineering.

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Low-Voltage D-C Measurements on Electrical Insulating Oils

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THE development work and experimental results presented herein have been a part of a co-operative project of the Utilities Co-ordinated Research, Inc. (Association of Edison Illuminating Companies) and the Massachusetts Institute of Technology. The purpose of this joint research project is the investigation of the mechanism of the deterioration of electrical insulating oils and the development of methods and apparatus for the study of this deterioration, with special reference to its influence on the electrical characteristics. It was for this reason that it was desirable to investigate the conductance of electrical insulating oils and methods of determining the conductance of such oils.

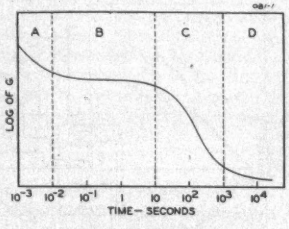

Figure 1. Variation of conductance with time at high gradients

General Considerations

In the usual conductance test for electrical insulating oils[1] the conductance is measured by means of a galvanometer used as an ammeter. A cell with a guarded electrode is used and from 500 to 1,500 volts potential difference is applied across the cell giving a potential gradient of from 200 to 1,200 volts per millimeter. The conductance (or resistance) is computed from the current reading one minute after the voltage is applied. As has been shown, principally by Whitehead,[2] this value is entirely empirical and often does not represent either the initial or the final conductivity of the oil. Using an amplifier-oscillograph and potential gradients of 500, 1,000, and 1,500 volts per millimeter Whitehead was able to measure the change of conductance with time from about 0.001 second after the application of voltage. The general type of the curve thus obtained for oils of low conductance is shown in figure 1.

Region *A* in figure 1 represents a brief initial decaying conductance indicating a phenomenon similar to dielectric absorption in solids. It has been suggested that it is due to the orientation of large polarized particles. Region *B* represents the true d-c conductance which is supposed to be due entirely to ions. It is this region which is of one to ten seconds duration in which we are most interested. Region *C* represents the time during which the ions are swept out of the space between the electrodes and space charges built up in the spaces near the electrodes. The empirical nature of the one-minute conductance value is easily understood since it falls in this region. Region *D* represents the long-time conductance after the "clean up" of the oil by the current which may take a period of hours to reach a constant value.

It was desired to find some more practicable and easier method than the amplifier-oscillograph arrangement by which to measure the true d-c conductance of region *B*. It was thought that the velocities of the ions could be reduced by reducing the potential gradient between the electrodes so that the true d-c conductance of region *B* would be extended from ten seconds duration to perhaps ten

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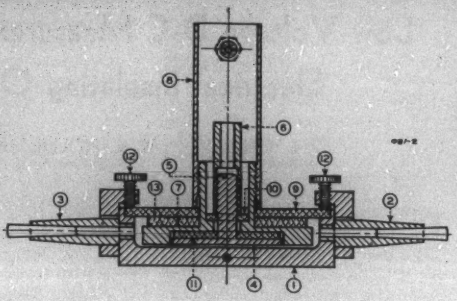
The authors wish to acknowledge their appreciation to the General Radio Company of Cambridge, Mass., for their hearty co-operation, and to R. F. Field of that company for his helpful advice in the development of the bridge herein described. The authors also wish to acknowledge the co-operation of the committee on insulating oils and cable saturants, Utilities Co-ordinated Research, Inc., Herman Halperin, chairman, and of the other committees representing the oil-refining and electrical-manufacturing companies.

1, For all numbered references, see list at end of paper.

Figure 2. Oil-measuring cell

1—Low electrode
2, 3—Filling arms
4—High electrode
5—Electrode stem
6—Tapped stem
7—Guard electrode
8—Shielding tube
9, 10, 11—Insulators
12—Clamps
13—Pyrex spacer



minutes duration. If, for example, the potential gradient were reduced from the customary 1,000 volts per millimeter to 10 volts per millimeter the duration of the true d-c conductance would be extended from ten seconds to more than ten minutes.

Measuring Cell

It was further desirable to be able to make measurements of the d-c conductance using the same low-capacitance cell (approximately ten micromicrofarads capacitance) used in this laboratory for power-factor measurements. By doing this, both a-c and d-c measurements could be made on the same oil sample under identical conditions of cleaning and filling. This cell is shown in figure 2. It is a three-terminal cell which is so constructed that it may be completely taken apart for purposes of cleaning. The cell used in the work herein reported was made of stainless steel with nickel arms for filling. The cell was cleaned by three washings in technical benzene and then dried for one hour at 100 degrees centigrade with a continuous stream of nitrogen passing through, and finally cooled in a desiccator.

Bridge

Using a General Radio type 544 megohm bridge upon which various alterations had been made so as to increase its range and to allow it to operate at low bridge voltages, it was shown that this type of an arrangement was practicable for use with bridge voltages of from one to ten volts. With various desirable improvements in mind a new bridge was designed and built specifically for the purpose of making conductance measurements. This bridge has the same essential circuit as the General Radio megohm bridge and is shown diagrammatically in figure 3. It consists of a high-resistance Wheatstone bridge with a vacuum-tube amplifier and sensitive galvanometer as a detector. B and N are high-ratio arms, B with a maximum resistance of a megohm and N with a maximum of 1,000 megohms. The arm A is a decade resistance unit ranging from 0 to 10,000 ohms in 0.1-ohm steps. The measuring cell is placed in arm P, the measuring electrode being connected to the high terminal by a shielded lead. The shield of this lead together with the guard ring is connected to the guard terminal which is grounded. The entire assembly is mounted on an aluminum panel and placed in a shielded case, which is also grounded. All switches in the actual bridge circuit are made of low-loss yellow bakelite and connections where perfect insulation is essential are air-insulated bus wires.

The switching arrangement of the bridge is controlled by the switch indicated as S. This is a four-pole double-throw switch with the points bent so as to make contacts in the off position as

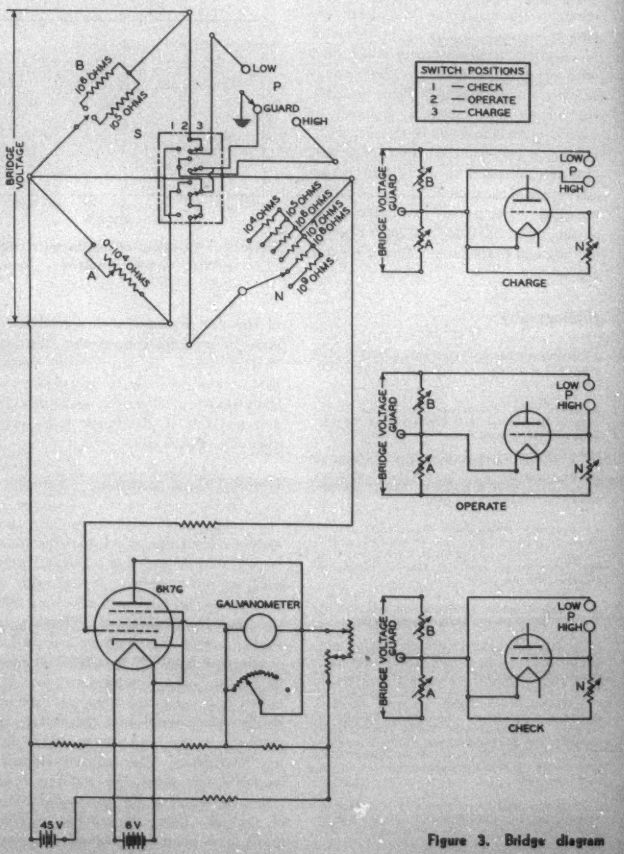


Figure 3. Bridge diagram

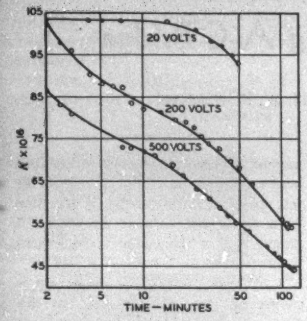


Figure 4. Specific conductance versus time

Table I. Specific Conductances of a Dewaxed Midcontinent Oil at Various Stages of Oxidation

Frequency	Cubic Centimeters O_2 Absorbed						
	0	69	143	187	217	256	328
Direct current	15	26	53	85	133	195	278
40	15	28	47	89	133	218	322
80	16	27	46	83	122	198	296
200	16	28	51	82	117	188	287
400	15	27	49	89	122	204	312
1,000	11	25	43	91	119	210	308

Values—$\times 10^{16}$; $T = 65$ degrees centigrade.

indicated by connections between the switch terminals. The usual off position then becomes the "operate" position of the bridge. The other two positions are indicated as "check" and "charge" positions. The "check" circuit allows the zero of the detector to be checked and adjusted, at the same time removing the bridge voltage from the measuring arm P. The "charge" circuit also allows the zero of the detector to be checked while leaving the bridge voltage across the measuring arm P so that measurements may be made from time to time with a continuous application of voltage to the measuring cell. This arrangement allows the time-decay of conductance to be measured from one to two minutes after the application of voltage, that time being necessary for the detector circuit and galvanometer to attain a steady state.

The 0.01, 0.1, and 1 megohm standards are accurate to 0.1 per cent and by connecting the proper open switch terminals of arm N to the low terminal of arm P it was possible to calibrate the 1,000, 100, and 10-megohm resistors to better than 0.3 per cent. The sensitivity of the detector is such that in measuring a resistance of the order of 10^{14} ohms the error is less than five per cent with about five volts applied. The detector sensitivity limits the value to which the bridge voltage may be reduced; this value also depending upon the resistance value of the oil-filled cell being measured. By the use of a more sensitive detector arrangement the accuracy of the bridge can be increased and the bridge voltage further reduced. It is obvious that the uses of this bridge are not limited to conductance measurements, but that it may also be used to measure almost any type of a high resistance up to 10^{15} ohms.

Guard Circuit

In this bridge the necessity for a conventional shield circuit is circumvented by the use of arms A and B as a shield circuit. The error in this method is negligible when measuring oils of low conductance and high resistance. However, as the value of the resistance between the guard ring and the low electrode of the cell decreases to approach the value of the resistance in arm B, the effective value of B will be accordingly affected. Since the resistance between the guard ring and the low electrode acts as a shunt around arm B, it is necessary in order to keep the error in arm B to less than 0.1 per cent that the value of this shunting resistance should be 1,000 times B or about 1,000 megohms. The resistance between the guard ring and the measuring electrode, which shunts around the detector, does not affect the accuracy of the bridge but may affect the sensitivity of the detector. Since the cell used in this work (figure 2) is so designed that the respective resistances between the guard ring and the measuring electrode and the guard ring and the low electrode are approximately the same as the resistance between the measuring and low electrodes, this guard circuit is quite satisfactory, and has the advantage of allowing measurements to be made rapidly. If it were desired it would be a comparatively simple matter to install a conventional shield circuit in the bridge.

Experimental Results

Two methods were chosen to show the value of low-voltage d-c measurements on electrical insulating oils. First, the change of d-c conductance with time was measured at various voltages and second, d-c measurements were compared with a-c measurements on the same oil sample. Through an inspection of these data, a few examples of which are presented here, a definite idea was obtained of the value of this type of a measurement.

Figure 4 shows the specific d-c conductances plotted against time for a heavy, dewaxed, solvent-refined, midcontinent oil[3] with bridge voltages of 20, 200, and 500 volts. It will be noted that with 20 volts per millimeter gradient (the cell spacing being 1.04 millimeters), a constant conductance was observed for a period of 15 minutes, while in the case of the higher potentials of 200 and 500 volts the conductance decreased rapidly with time from the initial two-minute reading. It is believed that these curves are thus an excellent confirmation of the theory expressed above, namely, that by reducing the potential gradient in the oil the velocity of the ions would be so reduced that the constant

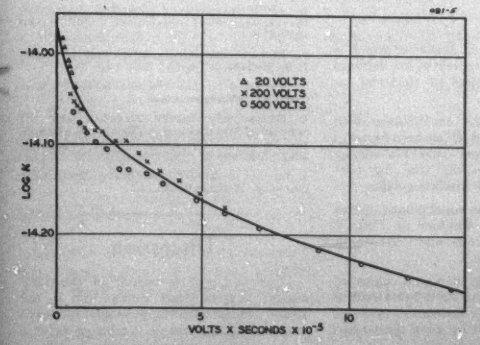


Figure 5. Logarithm of specific conductance versus (voltage × time)

conductance of region B in figure 1 would exist for a much longer period of time. This interpretation of these curves would lead us to conclude that low-voltage measurements of this type do measure the true d-c conductance of electrical insulating oils.

Figure 5 shows a plot of the logarithm of the specific d-c conductance (κ) of the same oil against the product of voltage (V) and time (t). For all three voltages the points fall along the same curve, showing that the conductance change depends upon the quantity of electricity passed through the oil. If we assume that this decrease in conductivity is due entirely to the discharge of ions at the electrodes, we can, by the use of certain other assumptions calculate the mobilities of the ions involved from the slope ($d \log_e \kappa/d(Vt)$) of a curve such as shown in figure 5. For this oil mobilities varying from 8×10^{-10} to 3×10^{-6} cm^2 sec^{-1} $volt^{-1}$ were thus obtained. These mobilities are of a reasonable order of magnitude, and these investigations are being continued.

Using the power-factor bridge[4] which has been developed in this laboratory, power-factor measurements were made on the same oil samples on which d-c measurements were made. By the use of the formula

$$\kappa = 0.556\times10^{-12}\nu \tan\delta C/C_0$$

where δ is the loss angle, C and C_0 are the capacitances of the cell with oil and air respectively as dielectrics, and ν is the frequency in cycles per second at which the measurement is being made, specific a-c conductances were computed for purposes of comparison with d-c values. Table I gives the specific conductances of a low-viscosity distillation cut of a midcontinent crude[5] at various stages of oxidation at 65 (±1) degrees centigrade. On inspection of these data it will be seen that there is, in general, good agreement between the d-c and a-c values, the average deviation from the mean being about five per cent. The deviations were thought to be due largely to fluctuations in temperature, and these fluctuations will be reduced in subsequent work. However, it is considered that these data do definitely show that the a-c losses are, in the case of this oil, wholly due to the same type of a loss which gives a d-c conductance and which is generally considered to be the result of ionic conductance. This type of a comparison is now being made on other oils that are being investigated in this laboratory. Since by this type of a comparison, low-voltage d-c measurements do account for all of the a-c losses it may again be concluded that the low-voltage measurements herein described do measure the true d-c conductances of electrical insulating oils.

Rapid-Recording A-C Bridge

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THIS paper describes a rapid automatic recording a-c bridge for continuously recording the power factor and capacitance during life runs or short-time tests on cables, capacitors, and insulating materials at a frequency of 60 cycles per second.

During the manufacture of electrical insulating structures and also during such extreme variations in conditions as occur on accelerated life tests, changes occur in the dielectric power factor and in the capacitance which are not fully reversible. A full record of such changes may be expected to contribute toward an understanding of the factors leading to failure under operating conditions. Data of this type in the past, generally were obtained manually, plotting point-by-point measurements made on a manual bridge. It is often desirable to obtain records of rapid changes which occur faster than can be recorded by this method. The automatic bridge described here rapidly records any change in the test specimen and is capable of operation 24 hours a day without attention. A photograph of the complete equipment is shown in figure 1.

A block diagram of the equipment is shown in figure 2. Referring to this diagram, a Schering bridge is used to measure capacitance and power factor. The voltage across the detector diagonal of the bridge, indicating bridge unbalance, is amplified and impressed upon circuits sensitive to components of the unbalance voltage produced by capacitance change and power-factor change respectively in the test specimen. These phase-sensitive circuits, called "phase selectors," control two thyratron circuits which supply power to two motors. The motors are coupled to adjustable circuit elements in the arms of the Schering bridge so that the unbalance voltage is reduced to zero and the motors are de-energized. Thus, the bridge is automatically balanced for the new values of capacitance and power factor which the test specimen has assumed. The time required for this operation is about one second. To prevent motor travel beyond the balance point because of the inertia of the motor armature in the oil thereby again leading to the conclusion that the low-voltage methods developed in this paper do measure the true d-c conductance of electrical insulating oils.

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Summary

1. Apparatus has been developed which is suitable for the measurement at low voltages of the d-c conductances of electrical insulating oils.

2. The change of d-c conductance with time of a highly refined oil has been found to substantiate the theory that low-voltage methods do measure the true d-c conductance of electrical insulating oils.

3. The change in the conductance of this oil is shown to be a function of $V\times t$, V being the applied voltage, and t the length of time of application.

4. D-c measurements have been compared with a-c measurements on a low-viscosity oil and low-voltage d-c measurements have been shown to account for all of the a-c loss

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Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

tures and the associated moving parts, an antihunting feature is built into the equipment.

The new positions assumed by the circuit elements are indicated on the capaci-

Figure 1. Rapid-recording a-c bridge

tance and the power-factor recorders, the pens of which are electrically coupled to, and move in unison with, the shafts of the bridge-circuit elements. The scales are marked directly in capacitance increase and in power factor. The recording Schering bridge consists of the following units:

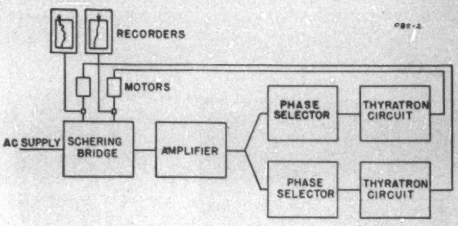
1. Schering bridge
2. Voltage amplifier
3. Phase selectors
4. Thyratron circuits and motors
5. Antihunting circuits
6. Recorders

The following is a brief discussion of the circuits and the principle of operation of each unit.

Schering Bridge

The Schering bridge is the conventional one shown in figure 3. A fixed resistor R_4 is shunted by an adjustable capacitor, and connected in series with a high-voltage standard capacitor, C_1. R_3 is a manually adjustable resistor in series with the specimen capacitor. Power-factor balance is obtained by setting the adjustable capacitor for balance. Capacitance change in the specimen is measured by adjusting a tap on a slide-wire resistor shunting the R_3 resistor until bridge balance is obtained. Guard circuit potential is adjusted by setting the resistor F to the point which allows push button B to be operated with no change in the "capacitance change" balance.

Figure 2. Block diagram of complete automatic bridge



A choice of several fixed resistance values at R_4 and a manually-operated step capacitor in parallel with the adjustable capacitor provide a means for selecting a power-factor range suited to the specimen tested. Range widths on the present bridge are 0.01, 0.02, and 0.05 tangent loss angle, which is approximately equal to the power factor or the sine of the loss angle. By use of the step capacitor, tangent loss angle as large as 0.3 may be measured, in which case the range covered by the recorder chart will be 0.25 to 0.30 tangent loss angle. Capacitance changes for full chart width deflection are 2½, 10, 25, and 100 per cent. When used with a 100-micromicrofarad standard capacitor, capacitances from 50 to 10,000 micromicrofarads can be measured. Larger capacitances may be measured with the aid of external shunts. A photograph of the motor-operated Schering bridge unit is shown in figure 4.

It is possible to test several specimens in succession by providing an adjustable resistor in series with each and a time switch for connecting the slide wire at R_3 successively to each.

Voltage Amplifier

The function of the amplifier is to increase the feeble unbalance signal appearing at the output of the bridge when unbalance occurs, so that sufficient voltage is available to operate the phase-selector circuits. With a few exceptions, it is a conventional three-stage amplifier with resistance and capacitance interstage coupling and transformer input, as shown in figure 5. A photograph of the amplifier and phase-selector unit is shown in figure 6.

For proper operation of the phase-selective circuits which follow the amplifier, the phase shift in the amplifier must be either zero or an integral multiple of 90 degrees and the output voltage must be relatively free from harmonics. Control of both is obtained by the insertion of resistance-capacitance attenuators R,C between stages. The need for these effects is explained later.

Series resistances are inserted in the leads to the grids of the second and third stages to minimize parasitic phase shifts. To minimize changes in amplifier performance produced by changes in tube characteristics if the tubes overload, all plate load resistances are chosen low. Amplifier sensitivity is controlled manually by potentiometer resistors in the grids of the first two stages.

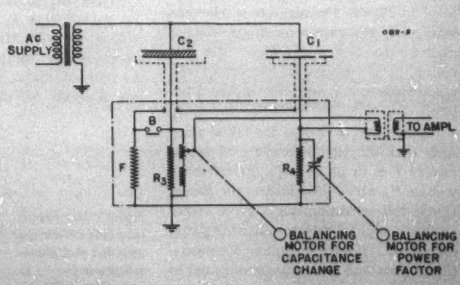


Figure 3. Circuit diagram of Schering bridge unit

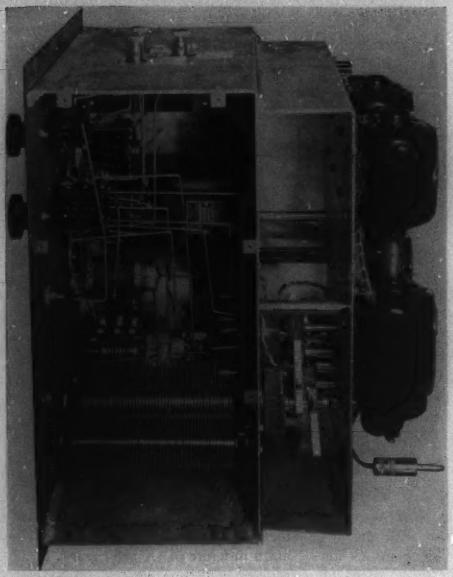


Figure 4 (left). Rapid-recording a-c bridge; Schering bridge unit

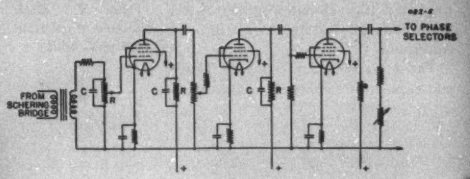


Figure 5. Circuit diagram of amplifier unit

Phase Selectors

The function of the phase selectors is to separate the voltage components of bridge unbalance produced by capacitance and power-factor changes in the test specimen. The amplified bridge unbalance voltage is simultaneously applied to both phase selectors, but a capacitance unbalance causes one phase selector to function while a power-factor unbalance actuates the other. If both quantities change in the test specimen, both respond. The amplifier and both phase selectors are mounted on one panel as shown in figure 6. For purposes of clarity, only one has been shown in the circuit diagram in figure 7.

The phase selector operates by comparing the phase and magnitude of the amplified bridge unbalance voltage applied to T, with the phase of a reference voltage E_R which is the a-c supply voltage used for the Schering bridge. For this reason, it is important to control the phase shift in the amplifier as noted before.

Assume that a change has taken place such that the signal to the grid transformer T is in phase with the reference voltage E_R which is applied to the plates. Under this condition, for a given signal voltage the phase selector gives its greatest output. For the instantaneous polarities of plate and grid voltage indicated in the diagram, tube 1 passes current during the half cycle that this condition is maintained. During the next half cycle, tube 2 passes current. Thus, a pulsating direct current passes through the common load resistor R_1, producing an average direct voltage across the output terminals leading to the thyratron circuit, the magnitude of which is proportional to the magnitude of the input signal to T. If the signal voltage is 180 degrees reversed, tubes 3 and 4 pass current through R_2, producing a voltage of opposite average d-c polarity across the output terminals. However, if the signal is in quadrature with the reference voltage, all tubes pass current during a portion of the cycle and the average direct voltage across the output terminals is zero. Under this condition, the other phase-selector circuit is actuated. The phase selector not described is identical except a 90-degree phase-shifting network is inserted ahead of the signal input transformer T.

The phase selector is not affected immediately by harmonics of the applied voltage, but it is necessary partially to filter out the harmonics present in the bridge unbalance voltage to avoid overloading the amplifier with these harmonic voltages, thereby decreasing the response to the fundamental bridge unbalance voltage.

Thyratron Circuits and Motors

The function of the thyratron circuits is to supply power to the balancing motors at a rate dependent upon the magnitude of the d-c output of the phase selectors. Both thyratron circuits are contained on one panel shown in the photograph in figure 8. The motors are mounted on the Schering bridge panel shown in figure 4.

A diagram of one of the thyratron circuits is shown in figure 9. The motor is series wound with a divided field winding, each field winding being connected in the plate circuit of a thyratron tube. The grid bias and plate-supply voltages,

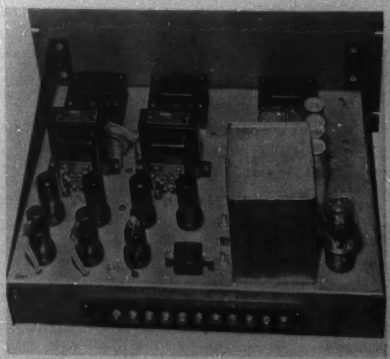


Figure 6. Rapid-recording a-c bridge; amplifier and phase-selector unit

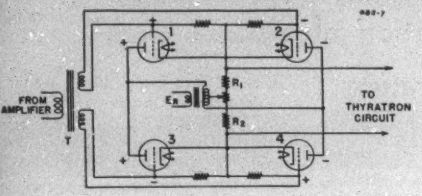


Figure 7. Circuit diagram of phase-selector unit

e_g and e_p respectively, are obtained from the 60-cycle a-c power supply. With d-c excitation on the grids, the tube with a positive grid fires or starts to pass current during each positive half cycle of the a-c supply voltage on its plate. This current persists until the end of the half cycle. If the d-c grid excitation changes polarity, the other tube fires, sending current through the other field winding and causing the motor to reverse direction. Speed of rotation is controlled as follows. For a high value of d-c grid excitation, the tube passes current during the full half cycle. For low excitation, the current impulse is shorter because the tube fires later in the half cycle. Hence, the average current through the motor becomes less and the motor runs more slowly.

The operation of the thyratron tube in this circuit can be explained as follows. The capacitor C_4 in the grid-bias transformer T_2 produces a constant phase shift in the alternating bias voltage e_g which lags the plate voltage e_p by about 90 degrees as shown in figure 10. Under this condition, the grid is at no time sufficiently positive to cause the tube to fire. With a slight positive d-c grid excitation superimposed upon the a-c bias, e_g is raised high enough to cause the tube to fire during the latter part of the positive half cycle of e_p. With increased d-c excitation, e_g is raised still higher so that the lowest point in this curve becomes sufficiently positive to cause the tube to fire, and the tube passes current for the full half cycle. Thus, regulated control of motor speed, depending upon the magnitude of the grid excitation voltage, is obtained.

Figure 8. Rapid-recording a-c bridge; thyratron unit

Antihunting Circuit

The function of this circuit is to prevent hunting produced when the inertia of the motor and associated rotating parts cause the motor to follow through or overshoot the correct position when the bridge balance is reached, thereby unbalancing the bridge in the reverse direction and setting up an oscillating condition.

A resistor R_4 and capacitor C_4 shown in figure 9 are inserted in the signal input lead to the thyratron circuit. These build up a temporary d-c potential in series with the signal voltage and opposite in polarity. This reduces the effective voltage at the thyratron grids and causes it to drop to zero slightly before the bridge has actually reached balance. The motor, by virtue of its inertia, then tends to coast to the proper position. Should the motor not stop at the correct position, the antihunting voltage quickly drops to zero, the signal voltage again takes effect, and the motor receives an additional impulse which finishes the balancing operation.

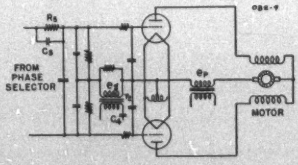


Figure 9. Circuit diagram of thyratron unit

Recorders

The function of the two recorders is to follow the position of the capacitance and power-factor balancing elements in the Schering bridge, thereby recording the capacitance and power factor of the test specimen as a function of time.

Each recorder has a separately excited ratio-type instrument movement excited from the a-c supply line through a resistance potentiometer mechanically coupled to the shaft of the balancing element in the bridge. The line voltage can vary as much as 20 per cent without affecting the indication. Chart speeds of one inch per minute and one inch per hour are provided.

Switches for changing bridge range, giving an alarm, or discontinuing the test may be located on the balancing elements to handle specimen changes larger than anticipated.

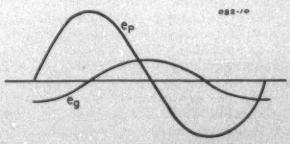


Figure 10. Grid and plate voltage relationship, thyratron unit

Summary

A power-factor and capacitance bridge capable of unattended recording has been described. Changes in the specimen may be fully recorded within one second of their occurrence.

The bridge may be used in connection with life tests, during treating processes, and for recording tests on large numbers of nominally identical structures, in the process of production.

The automatic control circuits described in this paper are not limited only to application to the Schering bridge, but may be used for automatic balancing of practically any other type of a-c bridge as well.

References

1. A New Phase-Angle Meter, W. Mikelson. *General Electric Review*, volume 41, December 1938, pages 557–8.

2. An Automatic A-C Potentiometer and Its Application to the Nondestructive Testing of Insulating Equipment, George Keinath. AIEE Transactions, volume 58, 1939, pages 887–90.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Effect of Load Factor on Operation of Power Transformers by Temperature

V. M. MONTSINGER
FELLOW AIEE

Synopsis: The practice of loading transformers by temperature is growing among operators who desire to take advantage of the additional capacity offered by this method of loading. The standards now recognize continuous overloads in cool ambients and short-time overloads under recurrent and emergency conditions.

The paper discusses the effects of different shapes of system load factors on the aging of the insulation. Then the ones that result in the greatest amount of aging are used for determining the permissible peak loads that can be carried safely with the same deterioration of its insulation as results from continuous operation at rated kilovolt-amperes.

A rational method of calculating the hot-spot temperature is shown by means of examples using a general average "time constant". The hot-spot temperature curve is then integrated to compare the aging with a given constant temperature.

From these results it is concluded that a normal power transformer can be overloaded 3 per cent for each 10 per cent that the system load factor is below 100 per cent. That is, for a 50 per cent load factor the permissible peak load is 15 per cent over the transformer rating in a standard ambient. For low ambients where 1 per cent overload for each degree that the ambient is below 30 degrees is now permitted, the permissible peak loads will vary depending on ambient and on load factor. By combining the 3 per cent rule for load factor and 1 per cent rule for ambient, proposed loading curves are shown for different load factors and different ambients.

SEVERAL papers have been written[1,2,3] on the operation of transformers by temperature during the past several years. As a result of these activities, the American Standards Association sectional committee on transformers, C-57 has published "Guides for Operation of Transformers" as an appendix to the proposed American standards for transformers, regulators, and reactors.

These guides give permissible overloads under the following conditions: (1) continuous overloads in cool ambients, (2) short-time overloads under recurrent conditions, and (3) short-time overloads under emergency conditions. These short-time overloads apply to transformers irrespective of the system load factors, and are limited to a few hours duration.

There are conditions under which the maximum load may last for times longer than those permitted for the overloads given in the guides, and where it is safe to carry some overload. It is primarily for this condition that this paper is presented.

Load Factor—Definition

The ASA definition for load factor (35.10.125) is as follows:

"Load factor is the ratio of the average load over a designated period to the peak load occurring in that period".

The ASA definition of peak load (35.10.135) is:

"Peak load is the maximum load consumed or produced by a unit or group of units in a stated period of time. It may be the maximum instantaneous load or the maximum average load over a designated interval of time".

"*Note:* Maximum average load is ordinarily used. In commercial transactions involving peak load (peak power) it is taken as the average load (power) during a time interval of specified duration occurring within a given period of time, that time interval being selected during which the average power is greatest".

Load factor as used in this paper refers to the load on the transformer bank under consideration. It is to be noted that load factor as so defined is to be distinguished from the ratio of the average load to the transformer rating, as this latter ratio is, by ASA definition, "capacity factor".

Very few power transformers operate at 100 per cent load factor, the majority of load factors being in the order of 50 to 70 per cent.

There are in general three types of loads, industrial, residential, and combined industrial and residential, all of which generally have load factors well below 100 per cent. Figures 1, 2, and 3 are good illustrations of such loads. These load factors are 51.5 per cent, 55 per cent, and 60.5 per cent respectively, based on peak loads of one-half hour, instead of on the extreme peaks.

Effect of Load Factor on Permissible Output

It is, of course, obvious that a transformer operating under low-load-factor conditions can carry some overload under peak load conditions with the same degree of aging of its insulation as one carrying rated load continuously. The problem is to determine the amount of overload that will give the same aging, for different load factors. To do this requires: (1) determination of the hottest-spot temperature during one complete 24-hour period, and (2) integration of the hottest-spot temperature curve during the 24-hour period, to obtain the amount of aging of the insulation. When an overload is found (by trial) to cause the same amount of aging as occurs when the transformer is carrying rated load for 24 hours, this represents the permissible overload for that particular kind of load curve.

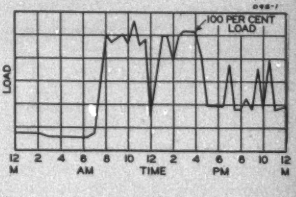


Figure 1. Industrial load, 51.5 per cent load factor

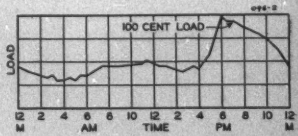


Figure 2. Residential load, 55 per cent load factor

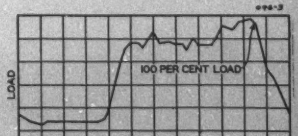


Figure 3. Industrial and residential load, 60.5 per cent load factor

Figures 1–3. Typical load curves on American Gas and Electric Company system

Paper 40-96, recommended by the AIEE committee on electrical machinery and standards co-ordinating committee number 4, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted April 4, 1940; made available for preprinting April 29, 1940.

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1. For all numbered references, see list at end of paper.

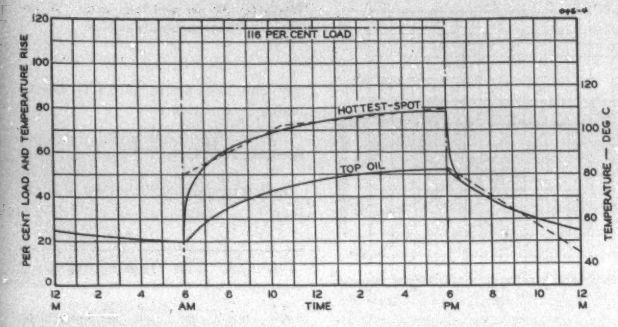


Figure 4. 50 per cent load factor composed of industrial load for 12 hours during 24-hour period

24-hour average load = 58 per cent; 30 degrees centigrade ambient

The permissible overload for a given load factor varies over a wide range, depending on the shape of the load curve. For example: a 50 per cent load factor in which 100 per cent load is carried 50 per cent of the time, with no load on the remainder of the time (figure 4) will permit a minimum overload rating, whereas a 50 per cent load factor in which partial load is carried most of the time and a peak load is carried the rest of the time (figure 7) will permit a greater overload rating. The first case might correspond to an industrial 50 per cent load factor condition requiring power during the day, only, and the second case, might correspond to a condition where, during the late evening hours, a heavy residential peak load is superimposed on a light 24-hour load.

Table I

Kva	High-Voltage Kv	B Time Constant
1,000	13.8	2.86
1,000	13.8	2.78
1,000	69.0	4.55
		3.39
2,500	13.8	2.83
2,500	69.0	4.0
2,500	138.0	4.46
		3.76
5,000	13.8	2.32
5,000	69.0	3.04
5,000	110.0	3.70
		2.89
8,333	34.5	3.03
8,333	69.0	3.23
8,333	138.0	4.55
		3.60
20,000	34.5	2.5
20,000	69.0	3.41
20,000	138.0	4.2
		3.37
33,333	69.0	3.03
33,333	115.0	3.20
33,333	138.0	3.65
		3.29

Calculation of Hottest-Spot Temperature

The hottest-spot temperatures are calculated in two stages. First, the top-oil temperature rise is obtained, and then the hottest-spot rise over the oil is determined and added to the top-oil rise. The most difficult part is the calculation of the oil temperature under varying load conditions. When this is done, the rest is easy, since the winding rise over the oil becomes constant in 20 to 30 minutes and can be taken directly from a curve of ultimate rise versus load, and added to the oil rise.

For the particular case under consideration the following assumptions are made, in calculating the hottest-spot temperatures.

1. The ratio of losses at rated load is 2:1 (2 copper, 1 iron).

2. The ultimate top-oil rise at rated load is 45 degrees centigrade.

3. The hottest-spot temperature rise over the top oil is 20 degrees centigrade (10 degrees average rise +10 degrees hot-spot rise over average rise) at rated load, and varies as the load raised to the 1.6 power.[1]

4. The no-load ultimate oil rise is 19 degrees centigrade. (The exact value based on 2:1 ratio of losses at rated load and temperature rise varying as 0.8 power is 18.7 degrees centigrade.)

5. The ultimate oil rise varies as the 0.8 power[1] of the losses.

6. The time constant corresponds to that for the average single-phase power transformer ranging in size from 1,000 to 33,333 kva. Table I.

7. One hundred per cent excitation voltage is on at all times. The time constant is, therefore, based on the copper losses only.

8. The load cycle selected is repeated from day to day such that the oil temperature is the same at the beginning and end of each 24-hour period.

9. A constant ambient temperature of 30 degrees centigrade is maintained.

Tests have shown[6,11] that the oil rise under transient conditions can be estimated quite closely by the exponential formula:

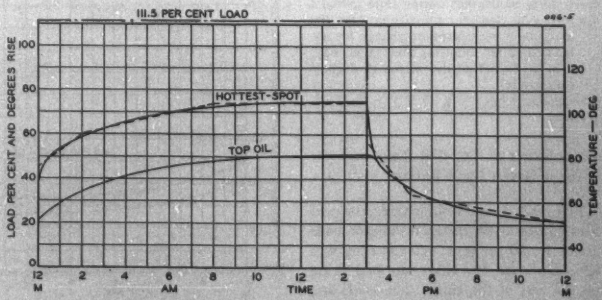
$$\theta_t = \theta_u\left(1-\epsilon^{-\frac{t}{B}}\right) \qquad (1)$$

where

θ_t = temperature rise of oil at any time t
θ_u = ultimate oil rise
$\epsilon = 2.718$
t = time in hours
B = time constant*
$= \dfrac{C \times \theta_u}{\text{loss at initial temperature}}$
C = thermal capacity of iron core, windings (copper) tank and oil
$= \dfrac{3.5 \times \text{pounds (core+copper+2/3 tank)} + 90G}{60}$
G = gallons oil (United States)

* The time constant is the time required to reach ultimate temperature rise, if all heat were stored in the transformer.

Figure 5. 62.5 per cent load factor; 30 degrees centigrade ambient



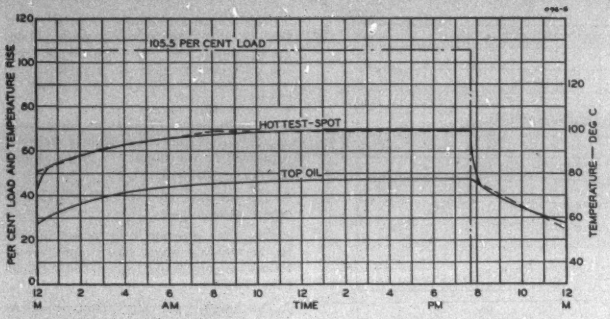


Figure 6. 82 per cent load factor, 30 degrees centigrade ambient

Only 2/3 of the tank is used because the lower third is comparatively cool, and 85.7 per cent (of 105*G* the correct value to use when the oil is at a uniform temperature) of the oil is used for the same reason.

In table I are some representative values of B for load (copper) losses only, taken at 110 per cent load. One hundred and ten per cent load was chosen for the reason that the overload periods exert the greatest effect on the life of the insulation, and 110 per cent load is a general average value used for the various load factors.

The average of the values of B in the table is 3.38. A general average value of 3.33 appears to be a reasonable one to use. It is proper to point out, however, that B varies to some extent for different oil rises for the reason that the oil rise is not proportional to the losses but varies as the 0.8 power of the losses. Tests show,[5] however, that results close enough for practical purposes are obtained by using an average value of B for the oil rises under consideration.

Equation 1 applies to oil-temperature rises. When the oil temperature is cooling down, the following equation applies:

$$\theta_c = \theta_i \left(1 - \epsilon^{-\frac{t}{B}}\right) \qquad (2)$$

Where

θ_c = cooling in degrees during time period t
θ_i = initial oil rise over the ultimate for the load under consideration (that is, for no-load condition following some given load, θ_i is the initial oil rise minus 19 degrees centigrade)
t = time in hours
B = 3.33

Calculation of Top-Oil Rise for a Given Load Factor

Figures 4, 5, and 6 show three assumed load curves in which the maximum loads are on for 50 per cent, 62.5 per cent, and 82 per cent of the time—no load being on the rest of the time. The loads are, therefore, 50, 62.5, and 82 per cent respectively. Figure 7 shows load curve with a 50 per cent load factor, made up of a 51.5 per cent load for 19 hours, and 140 per cent load for 5 hours representing a peak residential overload from 5 to 10 p.m.

As an illustrative case, the top-oil rise will be calculated for the 50 per cent load factor, figure 4.

It was found by trial that the oil rise is 25 degrees at the beginning and end of the 24-hour period. This gives a starting point of 25 degrees centigrade rise at 12 midnight.

From 12 to 6 a.m., the oil is cooling down. Using equation 2 we have (when $t = 6$ and the ultimate no-load oil temperature rise is 19 degrees centigrade)

$$\theta_c = \underset{\text{centigrade}}{\left(25 - 19\right)\left(1 - \epsilon^{-\frac{6}{3.33}}\right)} = 5.0 \quad \text{degrees}$$

Therefore, at 6 a.m. the oil rise has dropped from 25 to 20 degrees centigrade.

At 6 a.m. 116 per cent load comes on and the oil temperature starts to rise. The ultimate oil rise for 116 per cent load is 53 degrees centigrade. The oil rise at any time from 6 a.m. to 6 p.m. is estimated by equation 1, or

$$\theta_r = \left(53 - 20\right)\left(1 - \epsilon^{-\frac{t}{3.33}}\right)$$

Following are the oil rises, for different times t

Time	7 a.m.	10 a.m.	2 p.m.	6 p.m.
t =	1.....	4.....	8....12	
θ_r =	8.6.....	23.....	30....32.0 over 20 degrees rise (starting at 6 a.m.)	

From 6 p.m. to 12 midnight, the oil temperature again decreases:

$\theta_u = (52.0 - 19)(1 - \epsilon^{-\frac{6}{3.33}}) = 27.0$ degrees or 52.0 − 27 = 25.0 degrees centigrade rise at 12 midnight

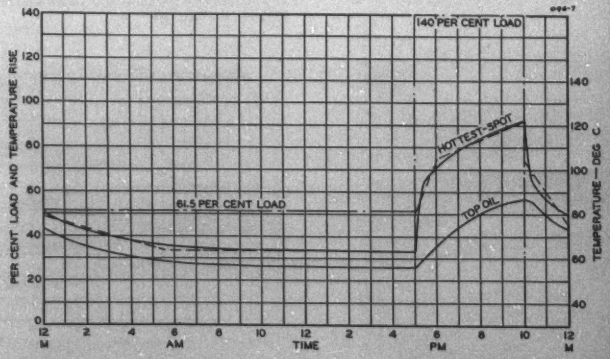
Adding 30 degrees centigrade ambient to the above values, we obtain the top-oil temperature as shown in figure 4.

The next step is to add the winding hottest-spot to the top-oil temperature curve shown in figure 4. The ultimate winding hottest-spot rises over the oil versus load are shown in figure 8, assuming 20 degrees rise at rated load.

The hottest-spot curve figure 4 is divided into trapezoids (dashed lines), for the purpose of integrating the area to determine the aging during a 24-hour period.

Figure 7. 50 per cent load factor, composed of light industrial and peak residential load

24-hour average load = 70 per cent, 30 degrees centigrade ambient



As shown in a previous paper,[10] the aging may be computed by the following equations:

For a constant temperature

$$A = te^{kT} \qquad (3)$$

where

A = aging units
e = 2.718
T = temperature degrees centigrade
k = 0.0865—which doubles the aging for each 8-degree-centigrade increase in temperature

For a trapezoid in which the two unequal sides represent temperature

$$A = t\left[\frac{e^{kT_2} - e^{kT_1}}{k(T_2 - T_1)}\right] \qquad (4)$$

where

T_2 = the maximum temperature degrees centigrade
T_1 = the minimum temperature degrees centigrade

As previously stated, the load-cycle conditions have been selected such that the aging will be the same as that under continuous rated load conditions. For a 24-hour period, the aging at 95 degrees centigrade (55 rise by resistance + 10 degrees hottest-spot + 30 degrees ambient) is by equation 3

$A = 24e^{0.0865 \times 95} = 87{,}500$ units

Integrating the hottest-spot (dashed) curve in figure 4, the aging by equation 4 is

$$A_1 = 6\left[\frac{e^{0.0865 \times 55.0} - e^{0.0865 \times 50}}{0.0865(55.0 - 50)}\right] = 570$$

$$A_2 = 4.5\left[\frac{e^{0.0865 \times 102} - e^{0.0865 \times 80}}{0.0865(102 - 80)}\right] = 13{,}650$$

$$A_3 = 7.5\left[\frac{e^{0.0865 \times 110} - e^{0.0865 \times 102}}{0.0865(110 - 102)}\right] = 70{,}000$$

$$A_4 = 6\left[\frac{e^{0.0865 \times 83} - e^{0.0865 \times 45}}{0.0865(83 - 45)}\right] = 2{,}320$$

Total 86,540 units

The figure 86,540 is close enough to 87,500 units since a change of one degree centigrade affects the aging approximately 12.5 per cent—based on the rate of aging doubling for each eight-degree-centigrade increase in temperature.

It is well to point out that "integration by parts" of the hot-spot temperature curve gives approximately correct results. That is, if in figure 4 the "time" is divided into one hour and one-half hour intervals (depending on the rate of change of temperature) and the average of these time interval hot-spot values is used for T in equation 3, the total aging units obtained are 86,980 which are within 0.5 per cent of those obtained by equation 4. In fact, when the hot-spot curve is quite irregular, the method of "integration by parts" is simpler and probably more accurate.

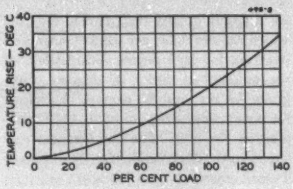


Figure 8. Hottest-spot winding rise over top oil

The aging of figure 7 is by equations 3 and 4:

$$A_1 = 5.5\left[\frac{e^{0.0865 \times 79} - e^{0.0865 \times 64}}{0.0865(79 - 64)}\right] = 2{,}800$$

$$A_2 = 11.5 \times e^{0.0865 \times 64} = 2{,}890$$

$$A_3 = 1\left[\frac{e^{0.0865 \times 100} - e^{0.0865 \times 80}}{0.0865(105 - 80)}\right] = 3{,}570$$

$$A_4 = 4\left[\frac{e^{0.0865 \times 121.5} - e^{0.0865 \times 105}}{0.0865(121.5 - 105)}\right] = 75{,}000$$

$$A_5 = 2\left[\frac{e^{0.0865 \times 105} - e^{0.0865 \times 75}}{0.0865(105 - 75)}\right] = 6{,}400$$

Total 90,660 units

Again, 90,660 units is close enough to 87,500 units—the aging at 95 degrees centigrade for 24 hours.

From the above results, it can be seen that the permissible overload for a 50 per cent load factor ranges from 16 per cent (figure 4) to 40 per cent (figure 7) depending on the character of the overload.* With shorter than five-hour peak loads imposed on partial load conditions, the permissible overload would be greater than 40 per cent. For a one or two-hour peak load, the permissible overload, considered only from the standpoint of aging, might be as high as 80 to 100 per cent. These heavy overloads might not be safe. In the first place, there are often limits other than aging of the insulation, such as overheating of lead joints (when soldered) and ratio-adjuster contacts, regulation, etc. In the second place, it has been shown[13] that when cellulose is maintained at temperatures above approximately 120 degrees centigrade chemical deterioration becomes an important factor.

Under a condition of this kind the short-time heavy overload should be limited to the time specified in the ASA guides. For example if, when following 50 per cent load, the overload was 1.4 times the rated load current the time should be limited to approximately 25 minutes for recurrent conditions and to approximately 100 minutes for emergency conditions.

General rules for overloading transformers should be safe for the worst condition, as one is not sure of the conditions under which these rules will be used.

An integration of the hottest-spot temperature curves shown in figures 5 and 6 gives maximum peak loads of 111.5 per cent with 62.5 per cent load factor and 105.5 per cent with 82 per cent load factor.

It is recognized that with water-cooled transformers the aging under low load factor might be more than for self-cooled transformers, because the oil temperature will respond more quickly to load changes. The difference, however, will not be very great since the faster oil cooling will partially compensate for the faster oil heating up.

The ASA recommended overloads as covered in the guides for operation of transformers, limits two-hour recurrent overloads to 10 per cent and 20 per cent, following full-load and no-load conditions respectively; also, emergency two-hour overloads are limited to 25 per cent and 40 per cent respectively.

The object of presenting the data in this paper is not to replace or supersede the ASA's recommendations which are

Table II. Permissible Loads for Self-Cooled Transformers (Per Cent of Rated Capacity)

Per Cent Load Factor	Ambient Temperature (Deg C)						
	0	5	10	15	20	25	30
50	145	140	135	130	125	120	115
60	142	137	132	127	122	117	112
70	139	134	129	124	119	114	109
80	136	131	126	121	116	111	106
90	133	128	123	118	113	108	103
100	130	125	120	115	110	105	100

* For the load curves shown in figures 1, 2, and 3, the permissible overloads are in the order of 25 per cent to give the same aging as for continuous operation at rated loads. In other words, the rating of the transformers could be 80 per cent of the peak loads.

Table III. Permissible Loads for Water-Cooled Transformers (Per Cent Rated Capacity)

Per Cent Load Factor	Ambient Temperature (Deg C)					
	0	5	10	15	20	25
50	140	135	130	125	120	115
60	137	132	127	122	117	112
70	134	129	124	119	114	109
80	131	126	121	116	111	106
90	128	123	118	113	108	103
100	125	120	115	110	105	100

not directly coupled with load factor, but rather to show what is possible under different load-factor conditions, and (most important) to point out the limitations to the use of overloads for various load factor conditions. Several utility engineers are calculating[7,8,9] the permissible overloads on distribution transformers under various conditions of service, and it is the hope that this paper will be of some benefit in these efforts.

We have seen that under the most severe conditions 16 per cent overload can be held on a transformer operating at its maximum load 50 per cent of the time, that is, 50 per cent load factor, figure 4. For 62.5 per cent and 82 per cent load factors shown in figures 5 and 6, 11.5 per cent and 5.5 per cent overloads respectively can be held.

Expressed in terms of load factor, we have:

Figure	Per Cent Load Factor	Per Cent Overload	Per Cent Overload for Each 10 Per Cent Reduction in Load Factor Below 100 Per Cent
4	50	16	3.2
5	62.5	11.5	3.07
6	82.0	5.5	3.05

It appears, therefore, that a safe rule would be to permit 3.0 per cent overload for each 10 per cent that the load factor is under 100 per cent. Approximately the same overload values were obtained in my 1930 AIEE paper,[1] although a different method of calculation was used.

As a result of my 1930 paper, the rule which allows one per cent continuous overload for each degree centigrade that the ambient is under 30 degrees centigrade for air, and 25 degrees centigrade for water, was incorporated in AIEE publication No. 100. The one per cent rule is now in the ASA Guides for Operation of Transformers.

This information will permit taking advantage of both low load factor conditions and low ambient conditions, in cases where this seems advisable.

The proposal is to combine the three-per cent rule and the one-per cent rule which will give the permissible peak loads in per cent of normal rating for low load factors and low ambients as shown in tables 2 and 3 for self-cooled and water-cooled transformers respectively.

The values shown in tables II and III are plotted in curve form in figures 9 and 10. It is not intended that these overloads relating to load factors, be added to the short-time overloads already permitted by the ASA Guides for Operation of Transformers.

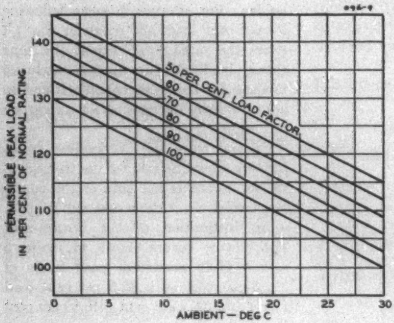


Figure 9 (left). Loading curves for self-cooled transformers

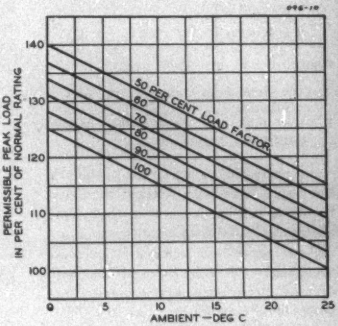


Figure 10 (right). Loading curves for water-cooled transformers

Future Work

To complete the work on loading power transformers by temperature, it is planned to present, at some future date, a paper showing how to convert any load cycle consisting of short-time high peak loads to the equivalent rectangular load cycle, and then limit its duration to the time given by the ASA guides.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Dead Points in Squirrel-Cage Motors

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Synopsis: Certain squirrel-cage motors are known to have a wide variation in starting torque depending on the angular position of the rotor. In extreme cases the torque may be actually negative at certain positions making the motor entirely useless. Various names such as "dead points," "cogging," and "locking" torque have been used to describe this condition but no detailed study of its mechanism appears to be available.

An analysis of the causes of such behavior is presented here as one of several phenomena not covered by classical theory since they arise from the nonsinusoidal nature of the air-gap field. It is shown (1) that only with certain definite relations of slot numbers can dead points exist at all, and (2) that, given one of these vulnerable slot combinations, the amplitude of the torque variation moves over an extremely wide range as the coil span is changed. The effect of coil span is not merely that due to the numerical change of harmonic chord factor but is shown to be the result of changes of direction of the various component forces. Test results confirming the analysis are included. It now becomes possible to correlate a great many apparently divergent results and to avoid troublesome combinations in future designs.

THE simple elementary theory of squirrel-cage induction motors treats the air gap field as a pure sine wave. Based on this simplification the classical laws of motor performance have been developed. It is evident, however, that in most actual motors the flux field differs sufficiently from a simple sine wave to warrant a closer study of its shape if the performance is to be predicted accurately. For example, the following phenomena depend largely on the nonsinusoidal nature of the flux field.

1. Vibration and noise.
2. Stray load loss.
3. Parasitic torques resulting in

(*a*). Asynchronous cusps in the torque curve.
(*b*). Synchronous locking at low speeds.
(*c*). Dead points or locking at zero speed.

While all of these subjects have been investigated to some extent, the dead-point phenomenon has probably received the least attention and no detailed study of its mechanism is available, at least in the English language. The present paper attempts to fill this gap, offering an explanation of the cause of dead points and some test results that confirm the analysis. It is shown that only with certain definite relations of slot numbers is it possible for dead points or locking torque to exist at all, and, further that the magnitude of the locking torque varies over an extremely wide range as the coil span is changed. While it is admitted that exact quantitative results are difficult to predict, a basis for judging the probability of trouble is established.

Paper 40-101, recommended by the AIEE committee on electrical machinery, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted November 8, 1939; made available for preprinting April 30, 1940.

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1. For all numbered references, see list at end of paper.

Test Observations

A motor which exhibits dead points, or cogging, as it has sometimes been called, will be found to have the following characteristics. The locked-rotor torque varies with the angular position of the rotor, passing through a cycle for each rotor slot pitch. If the running torque is measured slightly above and slightly below zero speed, the torque is found to agree quite closely with the *average* locked value. The locked torque, therefore, is a constant amount plus a variable component which has positive and negative values dependent on the rotor position. The net locked torque may be entirely positive or it may be zero or even negative at certain positions of the rotor. In the latter case the motor is truly "dead" and will not start even without load. However, when the torque is all positive it is only the minimum value that is useful for starting a load. Figure 1 shows tested values of locked torque for a motor of this kind.

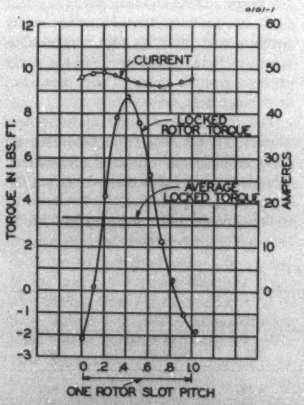

Figure 1. Typical test curve showing variation of locked rotor torque with rotor position

Motor had 24 stator slots, 18 rotor slots, 2 poles, 3 phases, 7/12-coil span, rotor-skewed one rotor-slot pitch

The variable component of torque is similar to the torque of a synchronous machine being dependent on the angular position of the rotor and passing through positive and negative half cycles. One is led therefore to search for a similar cause: two independent fields which are in synchronism at zero rotor speed and have distributions in space such as to give the required torque-angle characteristics. The following discussion shows that the necessary fields are present to fulfil just these requirements.

It has been observed further that motors having the same combination of stator and rotor slots may have widely different amounts of the variable torque component. Since most explanations of this phenomenon have been based heretofore on considerations of permeance variations, the observed results have appeared inconsistent. The analysis given here shows that these results can be explained.

Analysis

1. Stator Harmonics

As with many problems of this kind, it is sufficiently accurate to examine the harmonic fields of stator and rotor which result from the following assumptions:

(*a*). The slot currents are concentrated at points.

(*b*). The air gap permeance is uniform.

For integral-slot stator windings it is well known that the possible harmonics are:

$$n = 1 + MK \qquad (1)$$

where M is the number of phase belts per pair of poles, K is any positive or negative integer including zero. The algebraic sign of n shows the direction of travel with respect to the fundamental field. The velocity of each harmonic field is $1/n$th of the speed of the fundamental.

2. Harmonic Fields of Squirrel-Cage Rotors

A squirrel-cage winding carrying currents induced by the fundamental stator

field sets up harmonic fields of the following order in addition to its fundamental field.

$$m = 1 + KS_2 \qquad (2)$$

where S_2 is the number of rotor bars per pair of poles, K is any integer. Usually the only fields having sufficient magnitude to be of importance are those obtained by letting K equal plus and minus one.

This, however, does not complete the list of rotor fields. In addition to currents in the rotor bars induced by the fundamental stator field, there are currents resulting from each of the other stator fields. For each separate current component flowing in the bars there are the following fields:

1. The nth, corresponding to the nth stator field which induced the current under consideration

2. The mth, where

$$m = n + KS_2 \qquad (3)$$

In this case it is usually necessary to consider only the one or two lowest values of m resulting from any given value of n.

3. Comparison of Rotor and Stator Harmonic Fields

It is now possible to set down the harmonic fields of both members and compare them. For purposes of explanation it will be simpler to use an actual case and the one selected is a motor for which test data are available. The specifications are as follows:

Number of poles	= 2
Number of stator slots	=24
Number of rotor slots	=18
Number of phase belts (total)	= 6

Slots semiclosed for both members.

From these facts and the expressions for stator and rotor harmonics above, the orders of the various fields can be written as shown in table I.

The stator harmonics are simply those that occur in any three-phase motor having an integral-slot winding and the list could be carried out indefinitely. The first column under rotor harmonics is the series induced by the corresponding stator fields. These combine with the stator fields to produce true induction-motor torques, each with its own synchronous speed, and are of importance in the study of asynchronous cusps. They need not concern us here, however.

The remaining columns of rotor harmonics are the incidental fields set up along with the main fields of column one, their harmonic order numbers being determined by the number of rotor bars. It is these fields that are important in the present study. It will be noticed that in setting up a secondary field with fundamental distribution we incidentally produce 17th and 19th harmonics which have the same signs as the 17th and 19th stator fields. Thus there is a pair of 17th harmonic fields moving backward at $^1/_{17}$th of synchronous speed but maintaining synchronism with each other while the rotor is at rest, and there is a pair of 19th harmonic fields going forward at $^1/_{19}$th speed under the same conditions. There are, then, steady torques produced by each of these pairs of fields but the direction and magnitude of these torques and their dependence on rotor position will have to be investigated further.

Before going into these questions, however, we can take note of the fact that there are other such pairs of fields present. For each harmonic in the stator column, there is a corresponding harmonic in one or more of the rotor m columns.

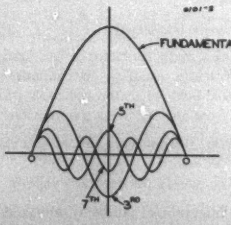

Figure 2. Relation of third, fifth, and seventh harmonics to the fundamental for a single coil

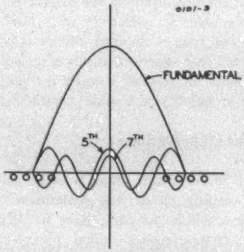

Figure 3. Relation of the fundamental, 5th and 7th harmonics for a three-phase winding with four slots per phase belt and full-pitch coils

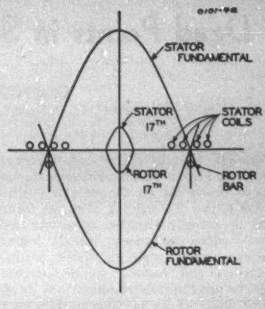

Figure 4a. Relation of 17th-harmonic waves of stator and rotor, for a particular coil span, with rotor in original position

Note: The 17th harmonic is drawn to an enlarged horizontal scale for clearness

4. The Phase Relations Between the Harmonics

In order to proceed with an analysis of the torque components it is first necessary to establish phase relations between the various harmonic fields. Figure 2 shows three of the component fields of a single full-pitch coil in relation to the fundamental. If there are several symmetrical phases of one coil each, this picture also represents the relation between the combined harmonics of all phases at the particular instant when the current in the coil shown is a maximum. It will be noted that those harmonics in the series 1, 5, 9, 13, 17, etc., have positive maximums coinciding. Those in the series 3, 7, 11, 15, 19, etc., have their negative maximums coinciding with the positive

Table I

Stator Harmonics	Rotor Harmonics				
n	n	$(K=-1)$ m_1	$(K=+1)$ m_1	$(K=-2)$ m_2	$(K=+2)$ m_2
+ 1	+ 1	−17	+19	−35	+37
− 5	− 5	−23	+13	−41	+31
+ 7	+ 7	−11	+25	−29	+43
−11	−11	−29	+ 7		+25
+13	+13	− 5	+31	−23	
−17	−17	−35	+ 1		+19
+19	+19	+ 1	+37	−17	
−23	−23	−41	− 5		+13
+25	+25	+ 7	+43	−11	

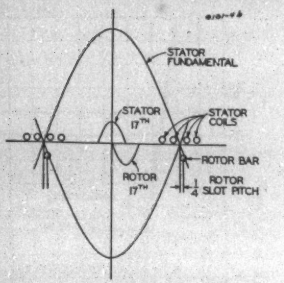

Figure 4b. Relation of stator and rotor 17th-harmonic waves after rotor has been moved one-fourth of a rotor-slot pitch

Table II. Magnitude of Torque Components for Different Coil Spans

n	m	Coil Span as a Fraction of Full Pitch 5/12	6/12	7/12	8/12	9/12	10/12	11/12	12/12
1	17	−11.70	+7.27	+ 1.15	−7.27	+7.27	−1.93	−4.52	+7.27
1	19	− 1.71	+8.42	−10.55	+8.42	−3.42	−2.24	+6.57	−8.42
5	13	− 0.27	+1.37	+ 1.28	−1.37	−0.19	+0.36	−1.13	+1.37
5	23	− 1.20	+5.70	− 7.12	+5.70	−2.26	−1.50	+4.52	−5.70
7	11	− 2.07	−1.00	− 0.17	−1.00	+0.41	+0.24	+0.58	+1.00
7	25	− 5.26	+3.38	+ 0.56	−3.38	+3.20	−0.35	−1.97	+3.38
11	7	− 1.47	−0.58	− 0.05	−0.58	+0.26	+0.15	+0.38	+0.58
13	5	− 0.15	+0.53	+ 0.49	−0.53	−0.07	+0.13	−0.41	+0.53
17	1	− 0.68	+0.41	+ 0.05	−0.41	+0.41	−0.11	−0.26	+0.41
19	1	− 0.09	+0.45	− 0.56	+0.45	−0.19	−0.11	+0.36	−0.45
23	5	− 0.52	+1.24	− 1.58	+1.24	−0.53	−0.32	+0.98	−1.24
25	7	− 1.58	+0.96	+ 0.11	−0.96	+0.90	−0.24	−0.55	+0.96
Totals		26.70	28.15	16.39	0.31	5.79	6.42	4.55	0.31

For each coil span the number of turns of the winding is changed to keep a constant fundamental flux density.

Table applies to case of 24 stator slots, 18 rotor slots, 2 poles, 3 phase.

maximum of the fundamental. The significance of this point will be seen later.

In general there will be more than one coil per phase belt in the stator and the coils will not be full pitch, both factors having an effect on the relations found for a single coil. In the case of the example previously used having four coils per phase belt it is found that the vector addition of the harmonic components of all four coils gives phase relations as shown in figure 3. Some harmonics are now found to be reversed and others remain as they were for a single coil. The process of finding which ones reverse is discussed in more detail in appendix *B*.

Proceeding to the case of chorded windings, it is found for the sample motor that the various harmonics again either reverse or hold their positions depending on the coil throw as discussed in appendix *B*. For any given stator winding, therefore, it is possible to draw the relation between the fundamental and any or all harmonics for a particular instant.

Considering the rotor for a moment we see that it is equivalent to a winding with one coil per phase belt and so can be represented by figure 2 for any one component of current.

5. The Torque Cycle for Any Harmonic

The next step in the analysis is to place the rotor and stator fundamental waves together with about the same phase relation that they might be expected to have normally with the rotor locked. This would be nearly 180 degrees apart, the actual angle depending upon the power factor of the secondary circuit and the ratio between magnetizing current and total current. For our present purpose the exact angle is not very important and so for simplicity the two fundamental waves will be drawn 180 degrees apart (figure 4*a*). The zero points of the stator wave pass through the center of a phase belt and the zero points of the rotor wave pass through the center of two bars, a pole pitch apart. Under these conditions the 17th harmonic of the stator will bear a fixed relation to the 17th rotor harmonic as shown. An instant later the fundamental waves will have moved slightly in a positive direction while the 17th harmonics will have moved $^1/_{17}$th as far in a negative direction. Thus the picture represents only a particular instant. Since the two 17th waves do not change their positions relative to each other, however, the torque between them, which is zero in this case, is constant.

Suppose now that the rotor be turned through one-quarter of a rotor bar pitch and a new picture be drawn for the same instant in time as before. Figure 4*b* shows this and it will be seen that the two fundamental waves remain in the same relation to one another. This must occur since the secondary current is induced by the primary and the time relation of the current in the bars simply changes to accommodate the new bar position. The 17th stator wave remains as it was but the rotor 17th is shifted relative to the rotor fundamental. The amount of the change can be visualized by going back to figure 4*a* and considering the position of the two rotor waves after the elapse of sufficient time for the fundamental to have moved one-quarter of a rotor bar pitch. This distance is 5 degrees of the fundamental wave or 85 degrees if referred to the harmonic wave length. During this interval the 17th wave will have moved 5 degrees of its own wave length in the opposite direction. The relative movement is thus 90 degrees. A change in rotor position of one-fourth of a bar pitch has therefore resulted in a change in phase relation of the stator and rotor 17th harmonic waves of 90 degrees. In this new position there is a torque exerted between the two fields tending to bring them in line with one another. By continuing the process of shifting the rotor slightly it can be seen that when a shift of one complete bar pitch has been made the relative position of the harmonic fields will have gone through a full cycle and the torque between them will have passed through a set of positive and then negative values.

If the 19th harmonic wave is examined it will be found to have the same properties so that it also produces torque depending on rotor position and goes through a complete cycle as the rotor is moved one rotor tooth pitch. This was one of the requirements of a theory that would agree with the known facts.

We have yet to investigate the effect of other pairs of harmonic fields and it is now proposed to examine the 5th harmonic. The rotor 5th harmonic wave has been shown to be a result of current induced in the rotor bars by the 23d stator harmonic. The relation between the rotor 23d and rotor 5th is shown in figure 5*a*. For the stator it is necessary to select a particular coil throw from which the relation of 23d and 5th can be worked out as shown in appendix *B*. This has been done and is shown in figure 5*b*. Now if the same assumption is made as before and we place the stator and rotor 23d harmonic fields 180 degrees apart, the two 5th harmonic waves fall in the positions shown in figure 5*c*.

The next step is to move the rotor to a new position and see what happens to the two 5th harmonic waves. If we select one-fourth of a rotor slot pitch for the first point as before we reason as follows. The 23d rotor field must bear the same relation to the 23d stator field in all positions of the

rotor since it is induced by it. The rotor must therefore be pictured as it would be after the lapse of sufficient time for the 23d harmonic to move one-fourth of a rotor bar pitch which is 5 fundamental electrical degrees or 115 degrees based on the 23d harmonic wave length. But during this period the rotor 5th harmonic would have moved 115 degrees of its own wave length since all waves move equal parts of their wave lengths in a given time. Converting both distances to degrees of the 5th harmonic wave and noting that both waves move in a negative direction the relative movement of the 5th with respect to the 23d and hence with respect to the stator 5th is,

$$115 - 115 \times 5/23 = 90 \text{ degrees} \qquad (4)$$

Here again we find that the 5th harmonic waves behave in the same manner as the 17th and 19th in that displacement of the rotor causes them to move apart and thus produce torque and the torque cycle requires a displacement of one full rotor bar pitch for its completion. In fact all harmonic pairs that exist follow this same rule.

This establishes a series of torque cycles, each arising from a particular harmonic pair and all existing simultaneously and having the same dependence on rotor position over a slot pitch. Two questions then remain to be answered. First, what are the magnitudes of the various torques? Second, what about the phase relations between the several torque cycles?

In answer to the first question, table II has been prepared from calculations on a particular motor by using the torque formula developed in appendix *C*.

The second question, that of phase relation of the torque cycles, is important and is responsible for some of the anomalous results that have been observed. It will be considered in detail in the following section.

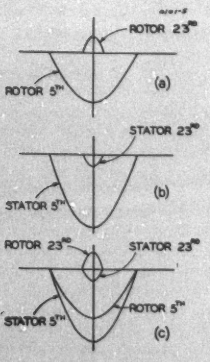

Figure 5

(a)—Relation of rotor 5th and rotor 23d

(b)—Relation of stator 5th and stator 23d for a particular winding

(c)—Relation of stator and rotor 5th-harmonic waves when the rotor 23d is induced by the stator 23d

Note: Waves are not drawn to scale

6. Relation Between the Various Torque Components

It is evident that there are two possible relations between the rotor and stator waves of a given harmonic when the rotor is in the position shown in figure 4*a*. The two waves are either in phase or 180 degrees out of phase. If they are in phase any movement of the rotor shifts their relative positions in such a way that the resulting torque tends to return the rotor to its original position. This, then, is a stable zero position. On the other hand if the rotor and stator fields are in direct opposition, movement of the rotor shifts the rotor field so as to produce torque assisting the rotor movement. In this case the original position is an unstable zero point.

Since all torque cycles repeat in the same space angle, they either add or subtract and all that remains to be done is to note whether the rotor and stator waves are in phase or out of phase for each harmonic in the original position. As noted above certain harmonics will be found to be one way and others the opposite way for any given winding. Table II has been arranged to show these relations for a specific case. The important fact brought out by this table is the way in which the coil span affects the final results. Thus for a given number of rotor and stator slots and phases there is a wide variation in the locking torque depending on the coil span used. This variation is partly due to the change in magnitude of certain harmonics but the more important cause is the cancellation of forces as a consequence of their phase positions.

Test Results

In order to confirm the theory developed here a two-pole motor having 24 stator slots and 18 rotor slots was wound successively with four sets of coils, each having a different coil span. The number of turns and the operating voltage were adjusted so that the fundamental flux density was the same in all cases. A test of the locked torque variation was made for each winding with two different rotors.

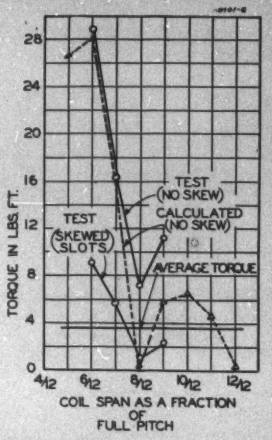

Figure 6. Amplitude of locked-rotor torque variation as affected by coil span. (The total spread between maximum and minimum torque is twice the amplitude shown here)

Curves apply to three-phase motors with 24 stator and 18 rotor slots per pair of poles

One rotor had no skew while the other was skewed a full rotor-slot pitch. The readings were taken at half rated voltage to avoid abnormal heating and consequent changes of resistance.

A sample set of test readings is plotted in figure 1 showing the torque variation as the rotor is moved through a rotor-slot pitch. A minor variation in current occurs also and a curve showing this is included. In figure 6 the amplitude of the torque variation for each of the tests has been replotted to show the effect of a change of coil span. A line showing the average value of the locked torque is included to emphasize the enormous variation that occurs with certain coil spans.

The calculated curve which is shown was worked out in accordance with appendix *C* and applies to the case of the straight-slot rotor. The agreement between test and calculated values, while not as close at all points as might be possible had more rigorous methods been used, seems to indicate that the analysis is essentially correct.

A number of such calculated curves have been worked out for other slot ratios and checked against available data from test files. In most cases fairly satisfactory agreement has been found. The effect of skew has not been calculated in detail but approximate methods of taking it into account can be devised.

In the interest of accuracy it should be

recorded that some of the tests, particularly those with no skew, showed an additional variation having a cycle of one-fourth of a rotor-slot pitch. No attempt has been made to account for this component of the torque variation but it is probable that accurate plots of the air gap flux would reveal the cause. Figure 8 shows this type of variation.

The calculated curve of figure 6 is applicable to any motor having the same number of slots per pair of poles as those used for this example provided the torque scale is adjusted to suit the particular values of current as set forth in appendix *C*. For all other three-phase slot combinations which have been investigated so far the general shape of the curve is similar, having minimum points at full pitch and two-thirds pitch.

It may be argued that once the causes

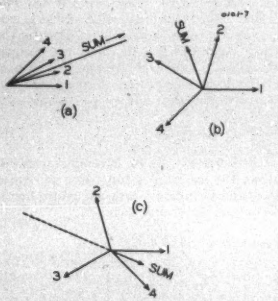

Figure 7

(a)—Summation of four fundamental vectors

(b)—Summation of four fifth-harmonic vectors

(c)—Summation of four seventh-harmonic vectors

of dead points are understood there should be little need to calculate their effects accurately since most designers will simply avoid slot numbers that produce them. The fact remains that other considerations may sometimes determine the slot numbers and thus a means of finding the best coil span is useful.

Rules to Avoid Dead Points

Since there must be stator and rotor harmonics of the same order traveling in the same direction to produce dead points, trouble can be avoided in the case of integral-slot windings by choosing a number of rotor slots which is not a multiple of the number of stator phase belts. For fractional-slot windings of the balanced type the rule is as follows: Avoid a number of rotor slots which is a multiple of the number of phase belts divided by Y, where Y is the denominator of the fraction, reduced to its lowest terms, expressing the number of stator slots per pole per phase.

If, for any reason, it is desirable to use one of these vulnerable slot ratios a coil span should be used that will minimize the dead-point effect.

A skewed rotor will always decrease the dead-point effect.

Previous Work

After the present study had been completed it was found that the idea of positive and negative signs for the torque components was not original but had been developed independently by Dreyfus[1] in Sweden. It was used later by Richter[2] in Germany and included in his "Elektrische Maschinen." Unfortunately there appears to be no English translation of either Dreyfus' paper or Richter's books and so their results have not had the appreciation in this country that they deserve.

A German investigator, Möller,[3] has taken a series of tests with various slot combinations. His tests showed strong locking with most of the combinations having a slot difference which is a multiple of the phase belts but he also got a weak locking torque in cases where the difference was a multiple of half the phase belts. The latter he attributes to a possible second harmonic of the slot pulsation. The coil span of the stator coils is not stated and no indication is given that its effect was considered important.

Gray[4] discusses the question of dead points and attributes the cause to permeance variations entirely. He shows a test on one motor in which most of the torque variation has a space distribution corresponding to a fifth harmonic of the rotor slot pitch. His motor has five stator slots for each four rotor slots but the numbers of poles, phases, and total slots are not given.

A discussion by Cotton[5] points to permeance variations as the principal cause and states that a common factor for slot numbers is to be avoided. Say and Pink[6] state that locking at standstill occurs when the stator and rotor slots are the same in number or if one is a multiple of the other.

The most recent reference to the subject before the AIEE occurred during the discussion of E.E. Dreese's[7] 1930 paper on synchronous running torques.

Appendix A. Magnitude of the Harmonic Fields

1. Stator

The magnitude of the stator harmonic fields which arise from the distribution of the winding can be calculated with fair accuracy by assuming that the slot current is concentrated at the center line of each slot and that the permeance is uniform. With these assumptions,

$$B_{Sn} = \frac{k_n}{nk_1} \qquad (5)$$

where

B_{Sn} = maximum value of nth harmonic field in terms of the fundamental field.

k_1 and k_n = product of pitch and distribution factors for fundamental and nth harmonic.

2. Rotor Fields

The magnitudes of the mth harmonics, or incidental fields of the rotor bear a fixed relation to the nth harmonic fields. The well-known relationship between the harmonic components of a rectangular wave is that the magnitude of each component is proportional to the reciprocal of its harmonic order. For two fields of orders n and m resulting from one set of currents the relation between them is,

$$B_{Rm} = \frac{nB_{Rn}}{m} \qquad (6)$$

where B_{Rm} and B_{Rn} are the magnitudes of the rotor mth and nth fields respectively. The problem then is first to find the value of B_{Rn}. One simple, approximate solution that suggests itself is to assume the rotor

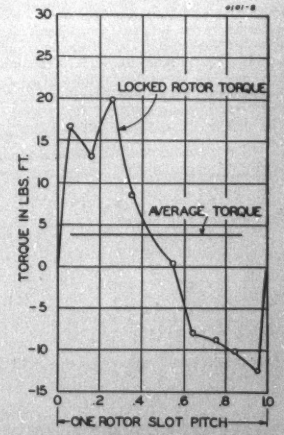

Figure 8. Typical test curve showing variation of locked-rotor torque with rotor position for motor without skewed slots

Motor had 24 stator slots, 18 rotor slots, 2 poles, 3 phases, 7/12 coil span

ampere turns equal the stator ampere turns. For the fundamental field or for some of the lower order harmonics this might be done without serious error, but when applied to cases where n is high and m is low it is soon apparent that this simple relationship is far from the truth. The reason for this is that the incidental mth harmonic fields produce flux linkages with the rotor bars which, in the case of a high ratio of n to m, become the determining factors in limiting the rotor current. A more nearly accurate method of finding the value of the rotor fields, though still an approximation, is to equate the rotor bar voltage set up by the stator nth field to the sum of the voltages due to the rotor nth and mth fields. Thus,

$$E_{Bn} = E_{Rn} + E_{Rm1} + E_{Rm2} + \dots \quad (7)$$

where,

E_{Bn} = rotor bar voltage induced by stator nth harmonic.
E_{Rn} = rotor bar voltage induced by rotor nth harmonic.
E_{Rm1} = rotor bar voltage induced by rotor m_1th harmonic.
E_{Rm2} = rotor bar voltage induced by rotor m_2th harmonic.

If we use B with its proper subscript to represent the maximum flux density of the various fields then, using per-unit notation,

$$E_{Bn} = B_{Bn} \quad (8)$$

$$E_{Rn} = B_{Rn} \quad (9)$$

$$E_{Rm1} = \frac{nB_{Rm1}}{m} \quad (10)$$

$$E_{Rm2} = \frac{nB_{Rm2}}{m} \quad (11)$$

which states that the voltages due to the nth fields are proportional to the magnitudes of those fields but that the voltage due to an mth field is n/m times the value of the mth field since the latter has a different space distribution. We noted before that:

$$B_{Rm} = \frac{nB_{Rn}}{m} \quad (6)$$

Thus we may write,

$$B_{Bn} = B_{Rn} + \left(\frac{n}{m_1}\right)^2 B_{Rn} + \left(\frac{n}{m_2}\right)^2 B_{Rn} + \dots \quad (12)$$

and,

$$B_{Rn} = \frac{B_{Bn}}{1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2} \quad (13)$$

The mth rotor fields are:

$$B_{Rm1} = \frac{n/m_1\, B_{Bn}}{1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2} \quad (14)$$

and,

$$B_{Rm2} = \frac{n/m_2 B_{Bn}}{1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2} \quad (15)$$

Expressed in terms of the fundamental stator field density, and the pitch and distribution factors, the rotor mth fields are,

$$B_{Rm1} = \frac{Kn}{m_1{}_1 \left[1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2\right]} \quad (16)$$

$$B_{Rm2} = \frac{Kn}{m_2 k_1 \left[1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2\right]} \quad (17)$$

Appendix B. Phase Relation Between the Harmonic Fields

If the fundamental fields due to each of the coils of a phase belt are added together the vector relations are shown in figure 7*a*. The vector representing the resultant field for the group lies at the center of the group of individual vectors.

A similar vector addition for the fifth harmonic fields of the phase group is shown in figure 7*b*. The angle between vectors is now five times the angle between fundamental vectors. Here again the resultant is located midway between the second and third vectors.

Figure 7*c* shows the addition of vectors for the seventh harmonic fields but this time the resultant vector is negative and therefore lies 180 degrees from the dotted line representing the center of the group.

Continuing with the other harmonic fields it is found that some have a positive resultant located along the center of the group while with others the resultant is negative. Thus with respect to the resultant fundamental field certain of the harmonic fields maintain the same phase relation that existed for a single coil while for others the effect of grouping a number of coils together in a phase belt is to reverse the phase relation of fundamental and harmonic. The term phase relation is used here to indicate whether at the point of positive maximum of the fundamental the given harmonic has a positive or a negative value. To find whether a given harmonic will reverse its position for a group of coils as compared to a single full-pitch coil it is only necessary to solve the expression for the sum of a group of vectors separated by a uniform angle and note the algebraic sign. If Σ is the resultant vector,

$$\Sigma = \frac{\sin N\frac{n\alpha}{2}}{\sin n\frac{\alpha}{2}} \quad (18)$$

where N is the number of vectors and $n\alpha$ is the angle between them. When Σ is positive the harmonic under consideration keeps the same relation to the fundamental that it has when a single coil is examined. If the sign is negative the harmonic reverses.

By a similar process the effect of chording the winding may be investigated. In this case the top and bottom layers of the winding are considered as two groups of coils displaced in phase by the angle by which the coil span differs from full pitch. The expression for Σ is solved for the case of two vectors differing by n times this angle and the algebraic signs determine whether or not the nth harmonic is reversed due to chording.

These relationships can be kept clear by using positive and negative signs for the distribution or breadth factor and for the chord or pitch factor. Thus the factor Kn in appendix *A* which is the product of these two factors will be either positive or negative. The torque formula in appendix *C* will also give either positive or negative results depending upon the algebraic signs of Kn and Km. Table II shows the torque components with their algebraic signs for a typical motor with various coil spans.

Appendix C. The Torque Formula

The torque developed between stator and rotor fields of the same harmonic order varies with the phase relation between them, reaching a maximum at 90 degrees. The maximum torque is proportional to the product of the magnitudes of the two fields. When dealing with several harmonics it must be kept in mind that for the same maximum flux densities the torques of various pairs of fields are also proportional to the harmonic orders. From these elementary considerations we may write:

$$\text{Torque} \propto m \times B_{Rm} \times B_{Bm} \quad (19)$$

for any one particular harmonic. Substituting the expressions for stator and rotor fields and including a proportionality factor the torque in per unit terms is,

$$\text{Torque} = \frac{K_n K_m \; I_L{}^2}{mK_1{}^2 \left[1 + \left(\frac{n}{m_1}\right)^2 + \left(\frac{n}{m_2}\right)^2\right] I_1 I_m \sin\theta} \quad (20)$$

where,

I_L = locked current
I_1 = rated current
I_m = magnetizing current
θ = phase angle between I_1 and I_m

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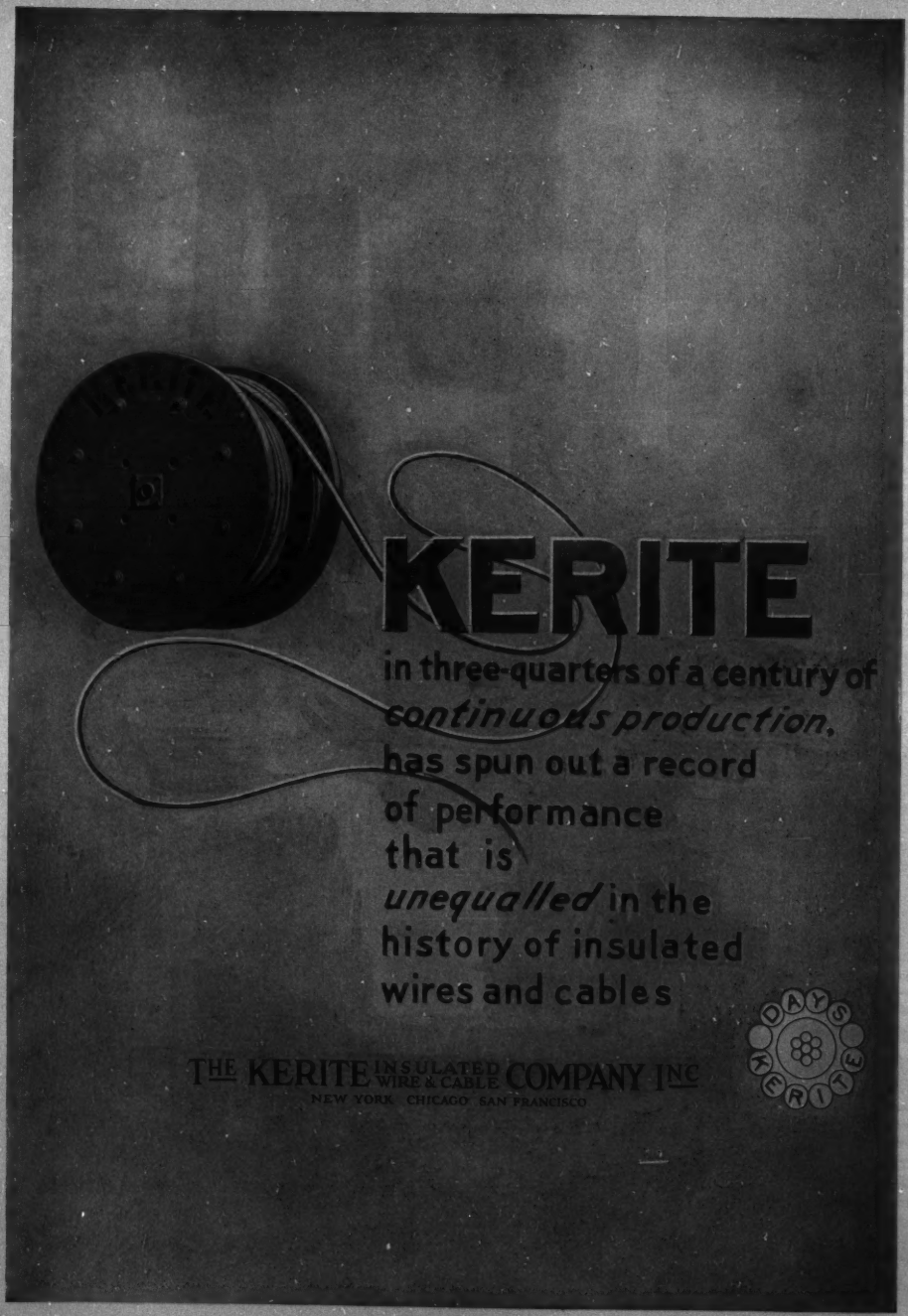
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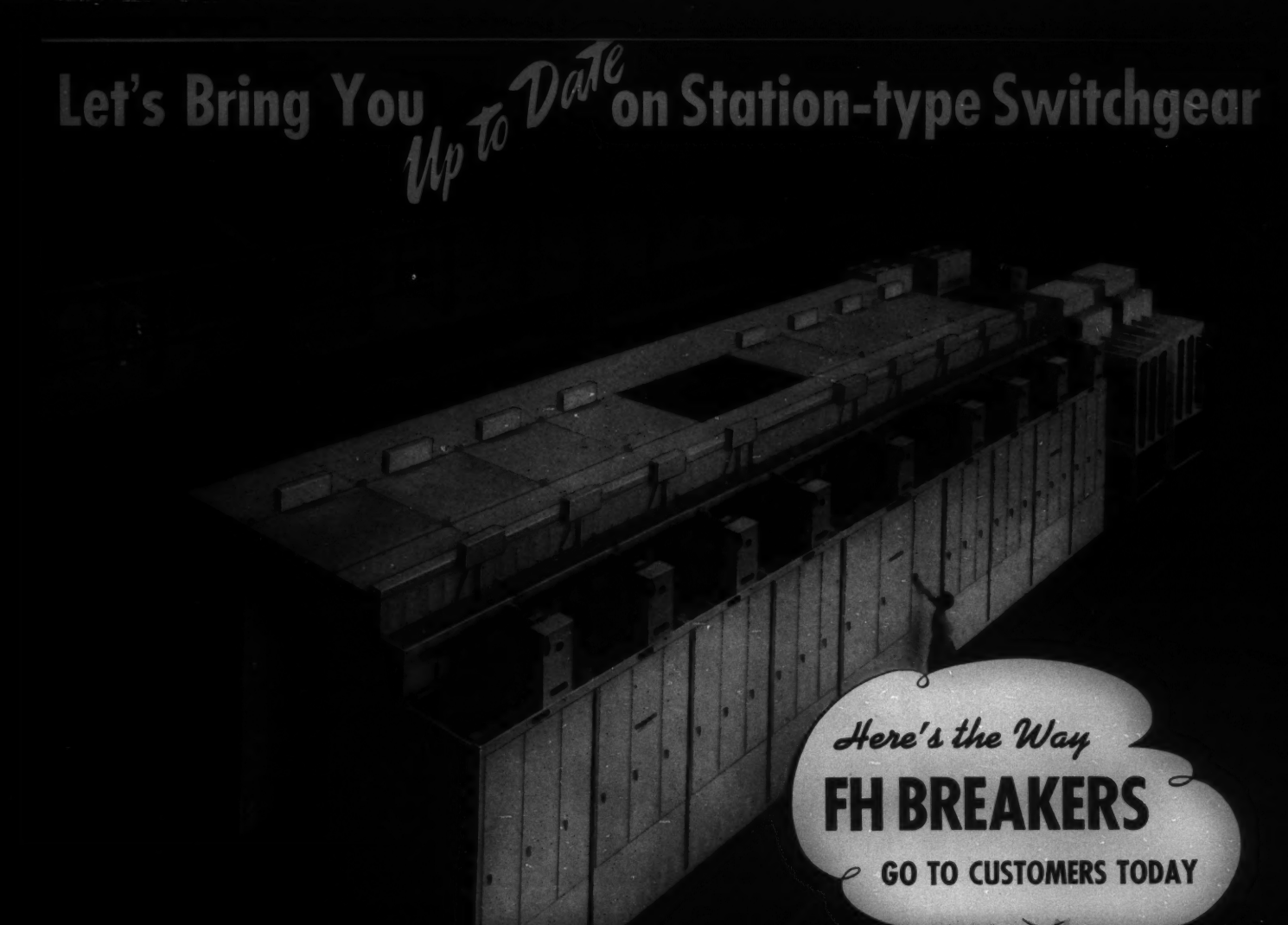

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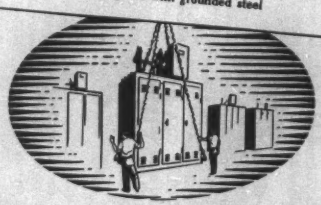

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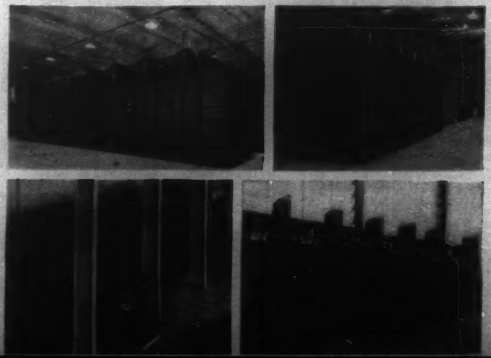

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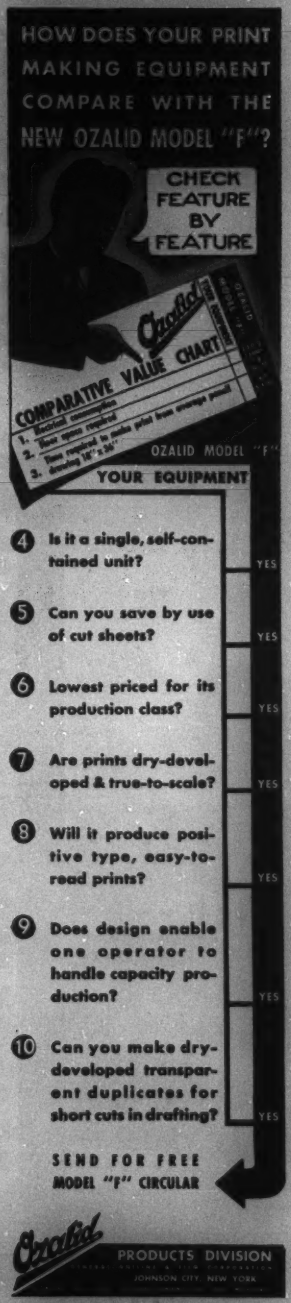
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Voltage Regulators.—Bulletin GEA 3443, 4 pp. Describes Pyranol induction voltage regulators available in a wide range of ratings. General Electric Co., Schenectady, N. Y.

Oil Circuit Breakers.—Catalog 3630, 8 pp. Describes outdoor oil circuit breakers of 7,500-volt rating and 50,000-kva interrupting capacity, for general distribution service. Roller-Smith Co., Bethlehem, Pa.

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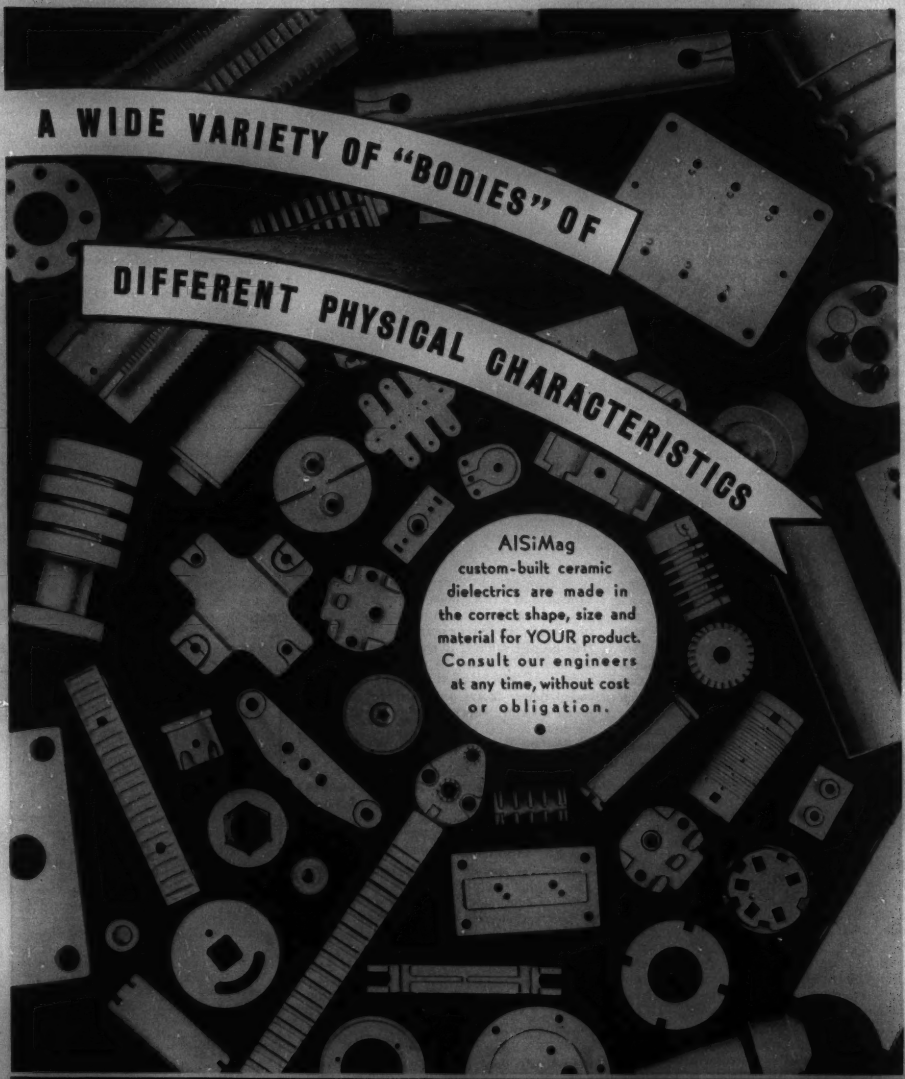
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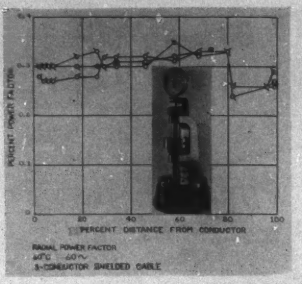

a large cable manufacturer and radial power factor graphs of a sample of the company's cable are shown in the accompanying figure. The three graphs distinguish measurements on the three conductors of a three-conductor cable. The slight break in the curves at 80% of the radial thickness corresponds to a change in tape thickness. For measurements above room temperature, the sample is warmed by heaters built into the electrodes. Temperature is measured by a thermocouple inside the upper electrode and welded to it, and by another in a well in the lower electrode. The potentials usually applied to the cell are between 200 and 1500 volts. A one-foot length of cable routinely supplies the samples for the radial power factor and related tests, but much shorter lengths can be used when necessary.

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(Continued on page 12)

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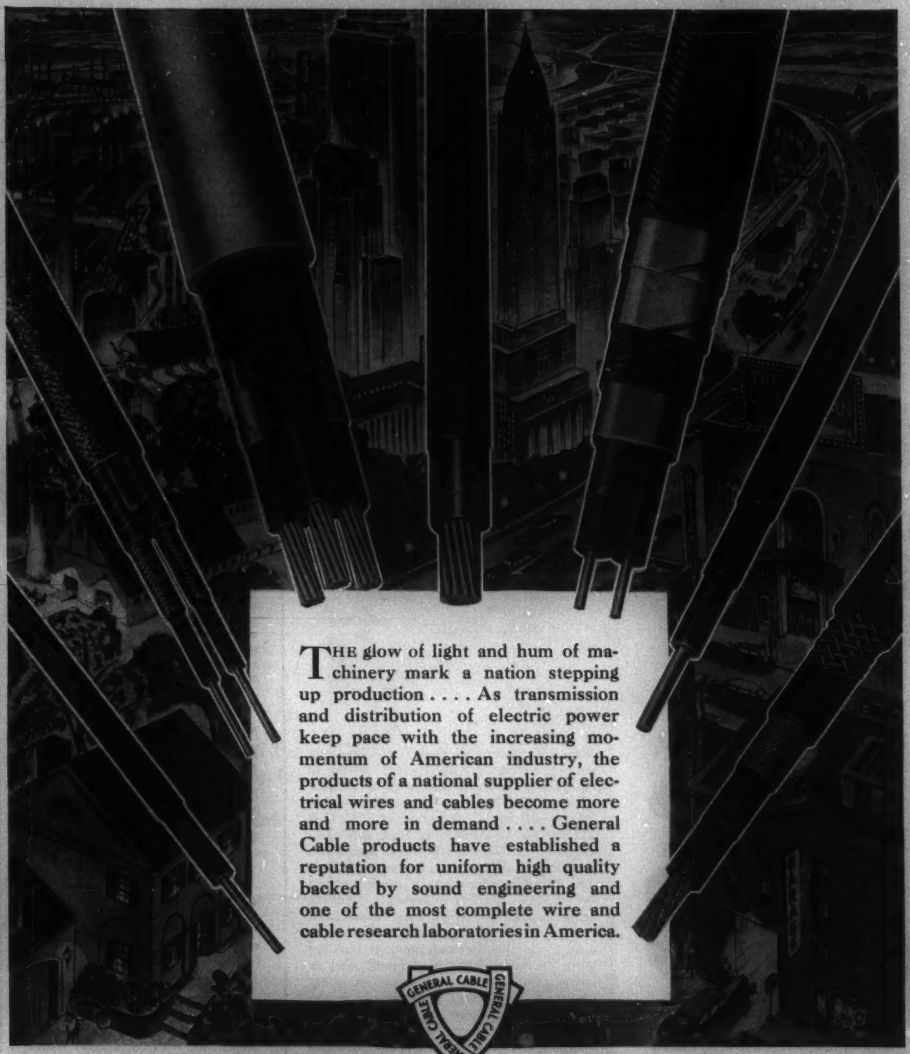
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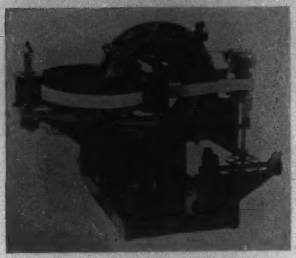

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The Acme Voltrol (made in portable and panel mounting types) gives complete manual control over line voltage in stepless range from 0 to 135 volts. Not a resistance type regulator, output voltage is independent of load.

Acme also manufactures Luminous Tube Transformers, Fluorescent Lamp Ballasts, Radio and Television Transformers, Mercury Vapor Lighting Transformers, Air-Cooled Power Transformers.

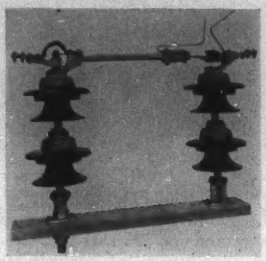
THE ACME ELECTRIC & MFG. CO.
22 Water Street • Cuba, N. Y.

Acme Electric
TRANSFORMERS

New Products

(Continued from page 10)

Side Break Switch.—This new, type "PMB-236" design by the Delta-Star Electric Co., Chicago, has multi-finger high pressure, button-type contacts formed to guide the joined ice and corrosion breaking contact member at the end of the tubular blade. When closed, the duronze arcing horns are separated but as the switch is opened, they make spring-pressure contact before the main contacts break and remain in contact for a part of the opening movement. The arc occurs on the horns, not between the blade and stationary contacts. According to the manufacturer, the simplicity of a single break, side opening switch, makes it ideal as a breaker disconnect or as a pole mounted sectionalizing switch on lines not warranting more expensive types. These switches are available in all standard voltage ratings to 115 kv. A 69-kv, 600-ampere unit is illustrated below.



Wire Calculator.—A pocket-size wire calculator, called the "Wirometer," for use in computing wiring problems in accordance with the 1940 National Electrical Code, has been developed in connection with the G-E Flamenol small diameter building wire campaign, by the General Electric appliance and merchandise department, Bridgeport, Conn. The Wirometer provides a quick method for arriving at code requirements. Among other information which may be obtained quickly by the use of the device is the conduit fill of all approved types of building wires, including wires of different sizes in one conduit; current capacities for wires when more than three wires are run in one conduit; corrections in current-carrying capacity for ambient temperatures over 30°C; and voltage drop for eight distribution systems. The Wirometer is available from G-E merchandise distributors.

Four New AIEE Standards

Revised Editions

•

No. 1 General Principles upon Which Temperature Limits Are Based in the Rating of Electrical Machinery ***Issued June 1940.***

This revision of the Standard No. 1 takes into account important recent trends in the development of insulating materials and apparatus—the effect on temperature limitations of new insulating materials and methods of treatment—greater use of protected equipment and the opening up of new fields of application.....Price 40 cents

•

No. 4 Measurement of Test Voltage in Dielectric Tests ***Issued June 1940.***

The latest developments in measurement of test voltages and wave shapes used in dielectric tests. Includes puncture tests, flashover tests and voltage proof tests—the use of alternating current, direct current and surge generators. An appendix covers testing equipment and arrangement. An extensive bibliography is included...Price 40 cents

•

No. 22 Air Switches and Bus Supports ***Issued June 1940.***

New standards applying to all types of air switches and bus supports above 600 volts for indoor or outdoor service. (Does not include air circuit breakers).....Price 40 cents

•

No. 45 Recommended Practise for Electrical Installations on Shipboard (Marine Rules) ***Issued July 1940.***

This new edition, a revision of the 1938 "Recommended Practise for Electrical Installations on Shipboard" will serve as a guide to the recognized requirements for the equipment of merchant vessels with electrical apparatus for lighting, signaling, communication, power and propulsion.....Price $1.50

•

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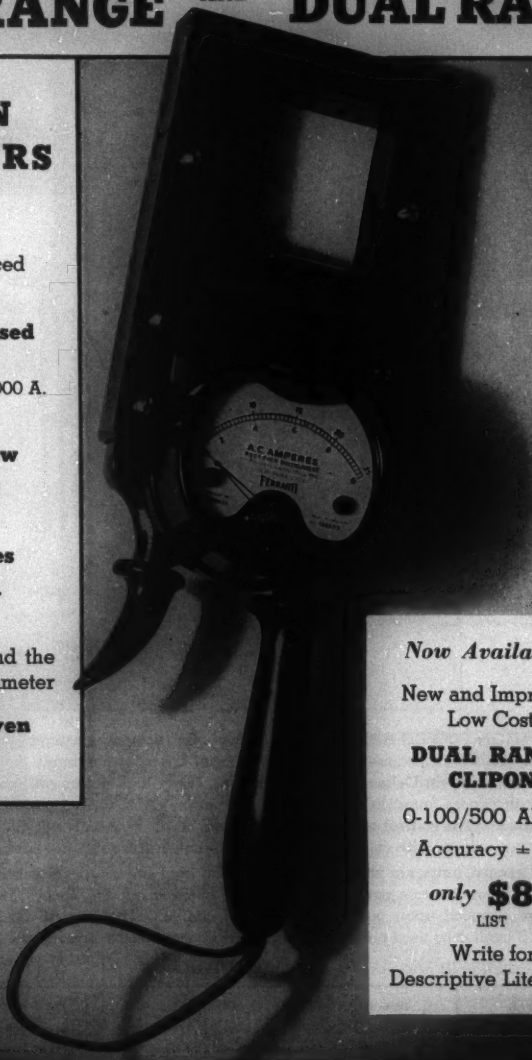

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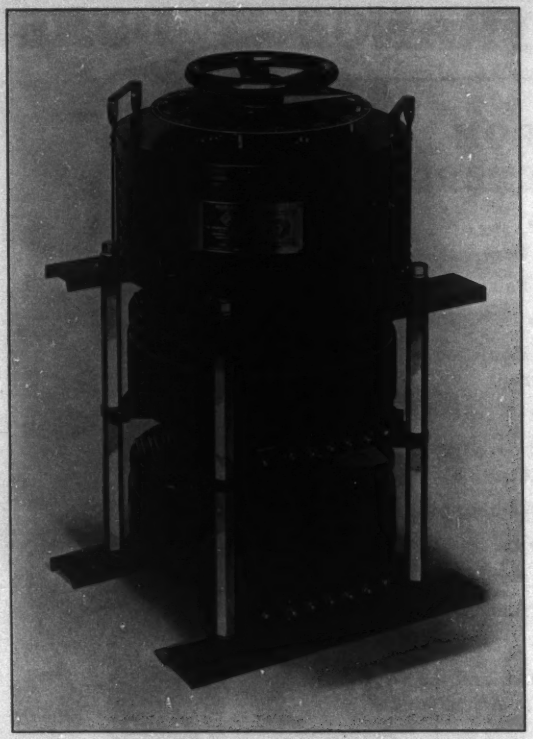
HIGH POWER VARIACS



FOR HIGH POWER APPLICATIONS two- and three-gang assemblies of the new Types 50-A 50-B VARIACS are now available on special order with prompt deliveries. When used on three-phase circuits in Delta or Wye connections, really high power can now be controlled with all of the conveniences found in the standard low-power VARIACS: excellent regulation; perfectly smooth and stepless control of output voltage from zero; very high efficiency; relatively small size; linear output voltage with calibrated dials; small temperature rise and advanced mechanical design.

The ganged units are shipped for table mounting unless specified otherwise. The standard shaft will accommodate a panel thickness up to one and one-half inches; longer shafts for thicker panels are supplied upon order without extra charge. The ganged assemblies of the Type 50 VARIACS cannot be used on vertical panels without auxiliary bracing.

Specifications

TYPE	DESCRIPTION	LINE VOLTAGE	MAX. CURRENT	LOAD RATING	PRICE
50-AG-2	Two Type 50-A	115-v*	45 amp	9 kw	$225.00
50-BG-2	Two Type 50-B	230-v*	31 amp	12 kw	225.00
50-AG-3	Three Type 50-A	230-v†	45 amp	18 kw	335.00
50-BG-3	Three Type 50-B	440-v†	31 amp	24 kw	335.00

* Delta (open or closed). † Wye.

Write for Bulletin 654 for complete information

GENERAL RADIO COMPANY

Cambridge, Massachusetts

BRANCHES: NEW YORK • LOS ANGELES

MANUFACTURERS of PRECISION ELECTRICAL LABORATORY APPARATUS

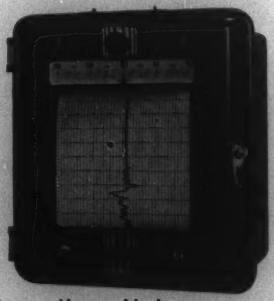
VIRGINIA PAPER MILL PEGS MACHINE SPEED

Chesapeake Corp. Installs Micromax Frequency Controller At West Point Plant

In operating its paper mill at West Point, Va., the Chesapeake Corp. has recently solved a power-load problem which sheds light on similar problems in other industries as well.

The Company's immediate need was for highly-constant speed of machines, because of the effect of speed on paper thickness and other quality factors. But, the machines are motor-driven, by power generated in the Company's own plant, and variable process-steam and electrical-load demand elsewhere in the mill was reflected in the frequency, so that machine speed was in turn variable.

First step in solving this problem was to plug a Micromax Frequency Recorder into the power circuit and



Paper-machine speed is okay now that frequency is under Micromax control at Chesapeake Corp.'s West Point, Virginia, plant.

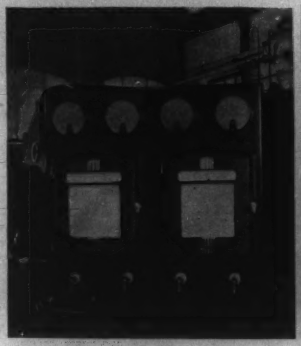
see just how erratic the frequency actually was. Finding extreme drifts in the order of a cycle, they asked us whether the same instrument, used as a controller, would correct the trouble.

We suggested they put a good operator on the push-button switch to the generator's governor motor, with instructions to watch the frequency chart and hold frequency as closely as he could. This was done, and until the man's efficiency was impaired by the close attention he had to give the job, the drifts were removed and frequency was held to within satisfactory limits. We knew that the Micromax Controller could hold equally satisfactory limits so control circuits were accordingly connected and regulation turned over to the instrument.

After a single day's operation, the Company's Chief Engineer congratulated us on the success of the equipment. That was 3½ months ago, and experience has served only to strengthen his confidence in the Micromax Controller's effectiveness and reliability.

The procedure used to solve this problem can be applied in any other power plant. It's not necessary for the user to have a technical knowledge of the Controller's operation, but the instrument is described both technically and practically in Catalog N-56-161(1) which will be sent on request.

RECORDING THE PULSE OF THE POWER SYSTEM



A thirty day record of frequency and another of load are drawn by these two Strip Chart Micromax Recorders at the Memphis Generating Company's Fourth Street Station.

Visible all over the operating aisle, this Round Chart Micromax records frequency at Detroit Edison's Waterman Station. Its big, black pointer makes it easy to read at a glance.

Write for Catalog N-57-161

HERE'S WHAT YOU'LL SEE IN BOOTH 18, POWER SHOW

Grand Central Palace, N. Y., Dec. 2-7

Showing how Micromax Recorders and Controllers are used in operating a power plant, L&N's exhibit in Booth 18 at the Power Show will bring out the many advantages of standardizing on Micromax. Measurements include generator, transformer, boiler and steam temperatures, CO_2, condensate purity, flow, smoke, load, frequency, voltage, power factor and many others. Micromax frequency and super-heat control and Metermax Combustion Control will be shown, as well as portable indicators, including the Optical Pyrometer, Universal pH Indicator, a temperature indicator and a conductivity instrument. See them all in Booth 18.

NEW TEMPERATURE CATALOG

Describes Micromax Temperature Recorders, which provide reliable guides for maximum safe loading of generators, synchronous condensers, frequency changers, large motors, transformers and cables. Ask for Catalog N-33-161.

Jrl Ad N-161(2)

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MEASURING INSTRUMENTS · TELEMETERS · AUTOMATIC CONTROLS · HEAT-TREATING FURNACES

THE Standards of the American Institute of Electrical Engineers now comprise forty-eight sections on electrical machinery and apparatus. They are chiefly devoted to defining terms, conditions, and limits which characterize behavior, with special reference to acceptance tests, and many of them are recognized officially as American Standards.

The Standards available are listed below, together with prices. A discount of 50% is allowed to Institute members (except on Nos. C57.1, 2 and 3). Such discount is not applicable on extra copies unless ordered for other members. Numbers of the Standards Sections should be given when ordering. A binder (illustrated above) for standards is available, with durable, stiff covers, resembling leather, lettered in gold. Price, $1.75 net.

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4	**Measurement of Test Voltage in Dielectric Tests (6-40)**	.40
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C57.1	**Transformers, Regulators and Reactors (1940)**	
C57.2	**Test Code for Transformers, Regulators and Reactors (1940)**	
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* *Approved as American Standard*

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SECTIONS IN PREPARATION

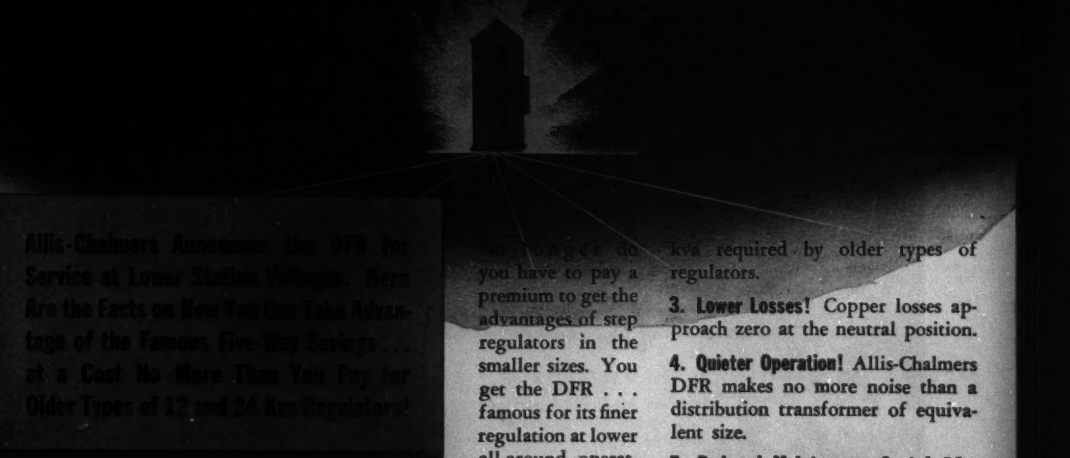
Seven such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6 Mercury Arc Rectifiers.	501 Test Code for D-C Machines.
24 Protector Tubes	40 Electrical Recording Instruments.
25 Fuses Above 600 Volts.	— Test Code for Synchronous Machines.
17g1A Letter Symbols for Electric and Magnetic Quantities.	

American Institute of Electrical Engineers — **33 West 39th Street, New York**

And now—

a new 12 and 24 KVA 5/8% step regulator!



Allis-Chalmers Announces the DFR for Service at Lower Station Voltages. Here Are the Facts on How You Can Take Advantage of the Famous Five-Way Savings . . . at a Cost No More Than You Pay for Older Types of 12 and 24 Kva Regulators!

Here's an announcement of importance to utility men with the profit viewpoint!

Since its introduction by Allis-Chalmers in 1933, system engineers like you have been specifying 5/8% Half-Cycling Step Regulators in an ever-increasing proportion. Now your demand has provided the operating experience and has increased production to the point where Allis-Chalmers offers the DFR Regulator for the 12 and 24 kva ratings at the *lowest price in history!*

No longer do you have to pay a premium to get the advantages of step regulators in the smaller sizes. You get the DFR . . . famous for its finer regulation at lower all-around operating costs . . . at a price no more than you pay for older types of regulators!

And that means you make your regulation dollar go farther in five ways . . .

1. Closer Regulation! Band width settings within ± 5/8% with "Feather-Touch" Control.

2. Lower Excitation Current! DFRs take only a fraction of the exciting kva required by older types of regulators.

3. Lower Losses! Copper losses approach zero at the neutral position.

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5. Reduced Maintenance Costs! No braking or holding devices. "Feather-Touch" Control with low energy circuits. Complete oil immersion of all moving parts.

Find out how the Allis-Chalmers DFR can cut the costs of regulation on your 12 and 24 kva lines. For complete information call the district office near you. Or write direct to Allis-Chalmers, Milwaukee . . . *today!*

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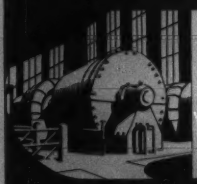
There is a "National" Brush grade for every type of transit service, including the heaviest duty service on modern, high speed equipment.



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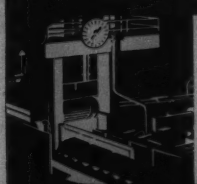
"National" brushes have established a reputation for reliability and outstanding performance on power generating and substation equipment.



STEEL MILLS

"National" brushes give dependable and economical performance under the varied and exacting demands of modern steel mill production methods.

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Minimum upkeep expense on commutating equipment is one reason for the preference given "National" brushes by factory maintenance men.

MINES

Many mines have improved performance of their electrified equipment by adopting "National" brushes for power, operating and transportation units.

NATIONAL

The performance characteristics resulting from careful study of the requirements of all types of electrical equipment, extensive research facilities and years of manufacturing experience enable users of "National" brushes to obtain maximum reliability and economy of operation.

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SPECIAL FEATURES AVAILABLE ON "NATIONAL" CARBON BRUSHES

- Glass Fabric Shunt Insulation
- Lead Coated Shunt Cable
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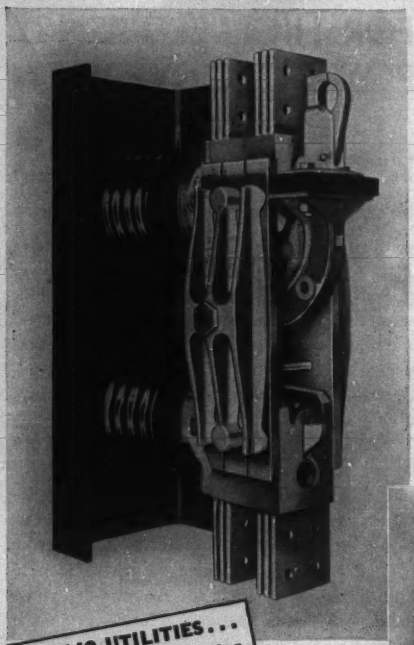
KLAMP-TITE SWITCHES used because they PAY



NO MAINTENANCE
Klamp-Tites do not need periodic inspection. They last for ages.

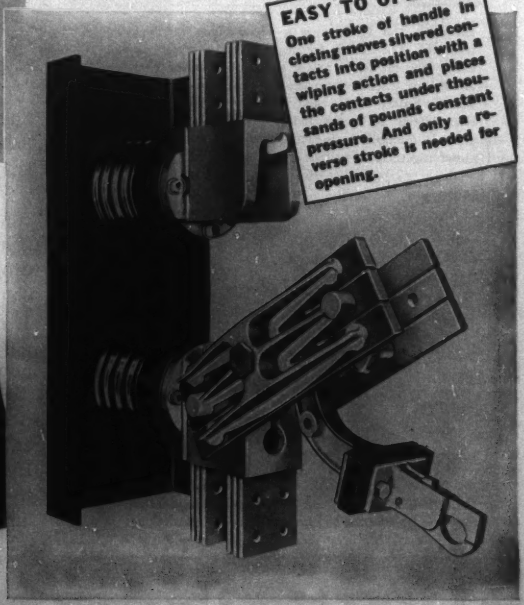
CONTACTS ALWAYS TIGHT
Built-in clamping feature holds contacts as securely as a bolted joint. Heavy bars carrying no current maintain enormous pressures indefinitely.

SAVE CURRENT
Current passes through Klamp-Tite contacts with almost no loss. Originally low, the millivolt drop remains low through years of service.

PUBLIC UTILITIES... STEEL MILLS and other industrial plants are now using many.

SAFE TO USE
Operating handle is outside the arcing zone in all stages of opening and closing.

EASY TO OPERATE
One stroke of handle in closing moves silvered contacts into position with a wiping action and places the contacts under thousands of pounds constant pressure. And only a reverse stroke is needed for opening.



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Klamp-Tites are available in wide range of styles and voltages from 1600 amperes up including styles for 23,000-volt service. Hook-stick, handle, or gang-operated as desired.

Ask one of our representatives, located in principal cities, or write for literature.

I-T-E CIRCUIT BREAKER CO., PHILADELPHIA, PA.

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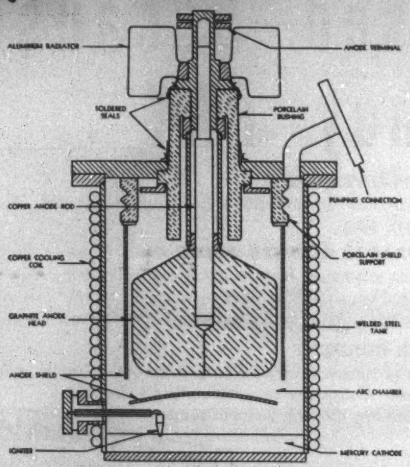
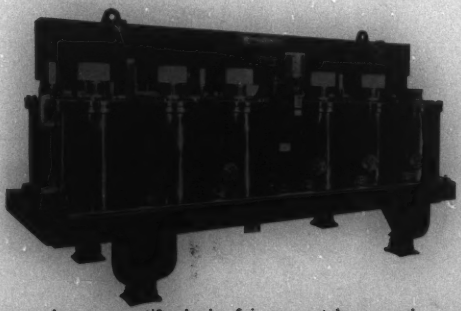
FOR HIGH-EFFICIENCY POWER CONVERSION



Basically, the Ignitron is a single-anode mercury-arc rectifier. The tube is fired by the igniter which, at the exact moment when power should be carried between anode and cathode, creates the cathode spot. Since there is no arc in the tank when the anode is negative with respect to the cathode, the need for shields and grids is minimized, and the electrodes can be placed closer together.



As a power rectifier, banks of six or more tubes are used. Ignitron Rectifiers require no expensive foundations—they can be adapted to almost any space restrictions.

A Westinghouse development that is finding growing use at voltages of 750 volts and less

A chemical plant is installing a 50,000-ampere unit. Another has recently ordered a 240,000-ampere unit. A Class I railroad uses a 3000-kw unit at its busiest terminal. Such are a few items from recent news about Ignitron Rectifiers.

The Ignitron Rectifier is a comparatively recent development whereby groups of individual tanks or tubes replace the single-tank, multiple-anode design of the conventional mercury-arc rectifier. Each tube contains a single anode and cathode, plus an igniter or "starter." An arc is established only when the anode is positive with respect to the cathode.

With this method of excitation, the anode can be placed closer to the cathode, and less shielding is required. With a lower arc drop, efficiency is higher than that of the conventional multi-anode design (about 1½% higher at 600 V; 2½% higher at 250 V). Cooling is simplified, and corrosion minimized.

Simplified voltage control with practically no change in over-all efficiency is another advantage of the Ignitron Rectifier. By varying the d-c voltage, it is possible to shift load, to start at low voltages or to limit current.

Westinghouse ENGINEERING RESEARCH FOR INDUSTRY

"NEVER SAW A CABLE TAKE PUNISHMENT LIKE AMERCLAD!"

ENGINEERS familiar with Amerclad find it hard to believe that anything made of rubber could be so tough. They've seen it dragged day after day through stony open-pit mines, run over by loaded mine cars, or exposed to water and grease and general machine-shop abuse. Yet it stubbornly resists damage, goes right on delivering power as though nothing had happened.

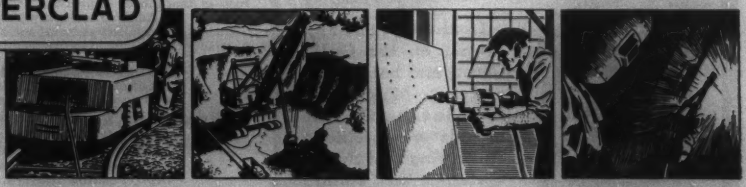
HERE'S AN INVITATION: Pick out your toughest portable cable job. Next time that cable needs replacement, replace it with Amerclad. You'll find that Amerclad has the stamina it takes to outwear your present cable. Often it outlasts two or three ordinary cables. And that means savings for you—both in replacement costs and lost time.

Amerclad owes its amazing toughness to a special rubber formula developed by years of research in the laboratories of the American Steel & Wire Company. Nothing but the finest Hevea rubber is used in its compounding. Its minimum tensile strength is 3500 lbs. per sq. in. Samples are required to stretch six times their own length before breaking. All Amerclad cables are vulcanized under enormous pressure, while encased in a heavy lead sheath that is afterward removed. This treatment bonds the rubber fillers and the jacket inseparably together to prevent tearing or stripping of the protective sheath.

AMERICAN STEEL & WIRE COMPANY **AMERCLAD**

IN THE MINES · ON ELECTRIC SHOVELS · FOR ELECTRIC TOOLS · FOR WELDING

Only genuine Amerclad Cables bear this identifying label, vulcanized right in the jacket. Make sure it appears on every cable you use in rough, abusive service.



AMERICAN STEEL & WIRE COMPANY

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VARNISHED CAMBRIC • RUBBER COVERED POWER CABLES • BUILDING WIRE

• SERVICE ENTRANCE CABLE • MAGNET WIRE •

ARMORED CABLE • FLEXIBLE CORDS • SIGNAL CABLE

CRESCENT IMPERVEX

MOISTURE RESISTANT RUBBER INSULATED BUILDING WIRE

It is made especially for use in damp locations in place of lead encased cable and is approved by Nat'l Elec. Code and Und. Lab. for such use.

Due to its smaller overall diameter and easier working characteristics, more wires of the same size or the same number of wires of larger capacity may be used in new wiring or rewiring existing conduits.

For more than seven years, IMPERVEX underground cables have been giving completely trouble-free service wherever installed, including the principal utility systems.

Send for Bulletin on CRESCENT IMPERVEX

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TRENTON, NEW JERSEY

Atlanta Kansas City | Baltimore Los Angeles | Boston Minneapolis | Buffalo New Orleans | Chicago New York | Cincinnati Philadelphia | Cleveland Pittsburgh | Detroit St. Louis | Indianapolis San Francisco

CRESCENT ENDURITE SUPER-AGING INSULATION • WEATHER-PROOF WIRE

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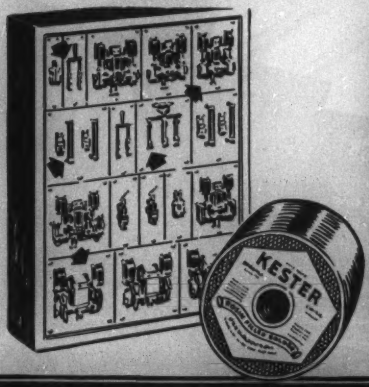

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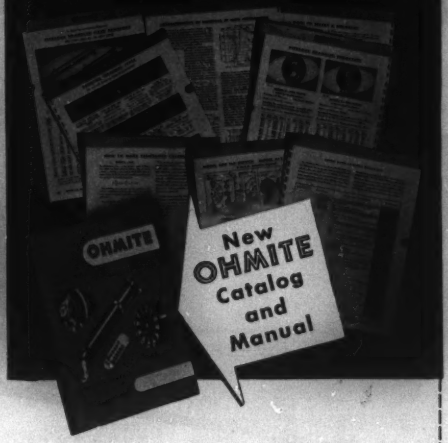

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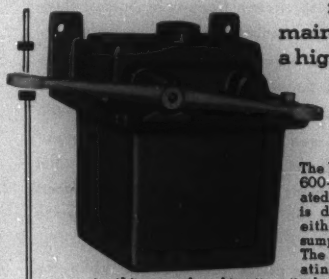

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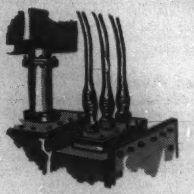
FOR OILTIGHT CONNECTIONS AND SPLICES



Oil Stop is suited to a wide variety of applications and has been used throughout the electrical industry for cable splicing, low cost oiltight terminals, stop joints, insulating buses, cementing transformer gaskets, repairing cracked bushings, coil sealing, waterproof coatings, etc.

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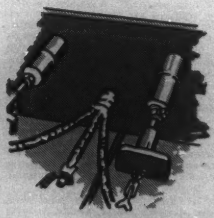

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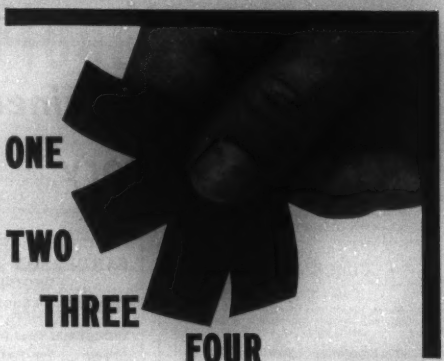

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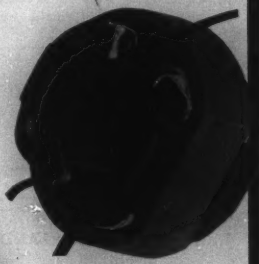

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In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

B.S.E.E., 1937; 28, single; 3 yrs exper util work; meter engr, meter and motor testg, draftg, statistical work, switchboard wiring. Employed. Desires engg position with future. E-720.

APPLICATION ENGR; M.Sc., M.I.T., 1930; G. E. Test Course; 37; exper in charge of des, estimating and specification writing of pwr, distr, control. E-721.

B.S.E.E., 26, single; 19 mos repair and installation of AC and DC coal mining machinery. Pwr switchboard installations. Pwr line constr. Available immed. E-722.

B.S.E.E., Carnegie Tech, 1932; married; N. Y. State professional engineer's license; 3 yrs pub util valuation and continuing property record work; 3 yrs des, prod, small transf, rectifiers. Employed. Desires engg pos with future. E-723.

ELEC DISTR ENGR; 46, good health; executive ability. 20 yrs util ind, exper all phases meters, relays, tests, distr work. Pos where cooperative initiative is required. Employed. Will locate anywhere. E-724.

RADIO ENGR; Master's degree; 10 yrs practice transmitter studio des oprn. Exper antenna field surveys. Installed large ultra high frequency network using frequency modulation. Capable executive; can handle men. E-725.

B.S., B.S.E.E.; 36, married. 7 yrs small motors and ventilating eqpt. 4 yrs air conditioning controls. Teaching exper. Desires engg pos requiring initiative and creative ability. E-726-216-Chicago.

GRAD E.E., 1926; 36, single; 19 mos G. E. Test Course; 10 yrs steam and diesel pwr plant oprn, indus maintenance, motor rewind, constr, some pub util exper. Speak Spanish. E-727.

ELEC ENGR, Fellow AIEE; exper in management of ceramic and light mfg; des and constr of high voltage stations and special purpose machines and processes; successful as sales engr. E-728.

E.E., Carnegie Tech, 1932; Reg Engr, W. Va.; 5 yrs elec problems coal mines (purchase to consumption) with consulting engg firm. Knowledge higher accountancy. Exper highway surveying. Now studying Spanish. E-729.

PLANT ENGR, E.E., 1922; 16 yrs indus plant constr, oprn, des, devpmt. N. J. Grade A oprtg license; now employed, desires application or constr pos with increased opportunities. Foreign language, German. E-730.

PWR AND LT EXEC; 42, married; 20 yrs constr, oprn, maintenance hydro-elec, steam-elec plants and substations; 2 yrs Puerto Rico. Location immaterial. E-731.

B.S.E.E., S.M.U., 1933; 28, married; 9 yrs exper with oil refinery and large util; system planning, des, economic studies, supervision overhead and underground constr. Desires permanent connection. Available immed. E-732.

B.S.E.E., N.Y.U., 1936; 25, single; 3 yrs experimental lab, motors, generator and various apparatus; studying motor des; now employed, desires pos with elec mfg or util with future. E-733.

E.E., middle-aged, excellent health, extensive exper large, small concerns, devpmt, shop, sales, chief engr several small cos. Listed "Who's Who in Engineering". Now employed Government, desires return industry. E-734.

INDUS ENGR; 42, married; routing, planning, time study, wage incentive, estimating, mfg, estimating costs. Capable exec, elec and mech. Now employed. E-735.

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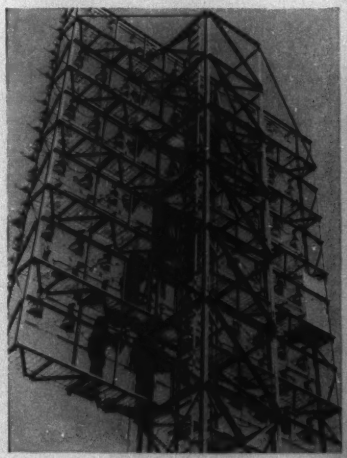

↑**CLOSE-UP VIEW** of a floodlight cluster. Eleven arms, each 26 feet long, cantilever on either side of the tower shaft to support 132 lights. Each level is framed with a maintenance platform and safety railings. An access ladder extends the full height of each tower.

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General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

WELDING WIRE
American Steel & Wire Co., Cleveland, O.
General Electric Co., Schenectady, N. Y.
Roebling's Sons Co., John A., Trenton, N. J.

WIRES AND CABLES
Aluminum
Aluminum Co. of America, Pittsburgh
Armored Cable
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Asbestos Covered
American Steel & Wire Co., Cleveland, O.
General Cable Corp., New York
General Electric Co., Bridgeport, Conn.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Bare Copper
American Steel & Wire Co., Cleveland, O.
Copperweld Steel Co., Glassport, Pa.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Roebling's Sons Co., John A., Trenton, N. J.
Bronze
Copperweld Steel Co., Glassport, Pa.
Copper Covered Steel
American Steel & Wire Co., Cleveland, O.
Copperweld Steel Co., Glassport, Pa.
General Cable Corp., New York
Flexible Cord
American Steel & Wire Co., Cleveland, O.
Belden Mfg. Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Heavy Duty Cord
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Lead Covered (Paper and Varn. Cambric Ins.)
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Okonite-Callender Cable Co., Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Magnet
American Steel & Wire Co., Cleveland, O.
Belden Mfg. Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Roebling's Sons Co., John A., Trenton, N. J.
Rubber Insulated
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Tree Wire
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.
Weatherproof
American Steel & Wire Co., Cleveland, O.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
Copperweld Steel Co., Glassport, Pa.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

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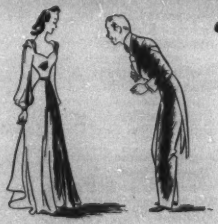

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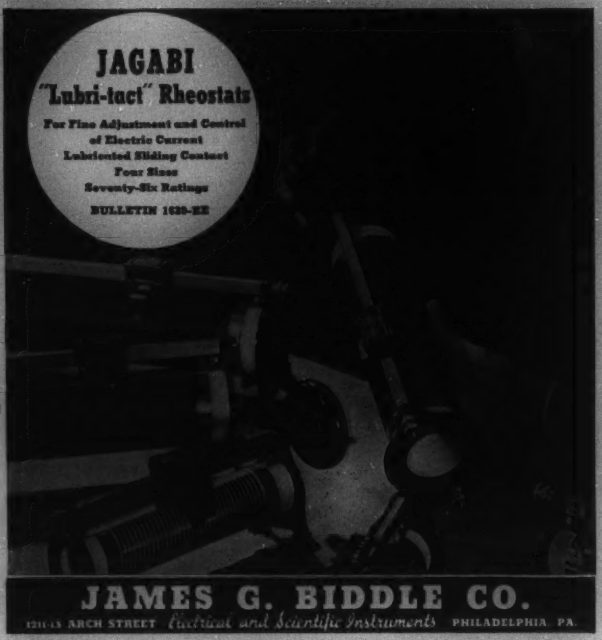

RECOMMENDED PRACTISE FOR

ELECTRICAL INSTALLATIONS ON SHIPBOARD

(MARINE RULES)

Section No. 45, AIEE Standards

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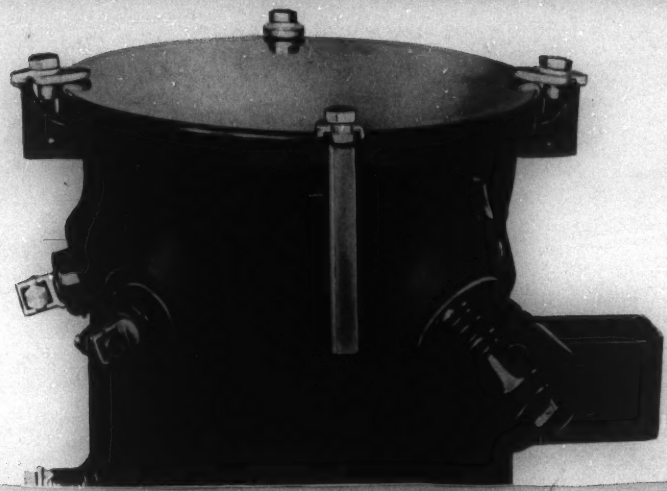

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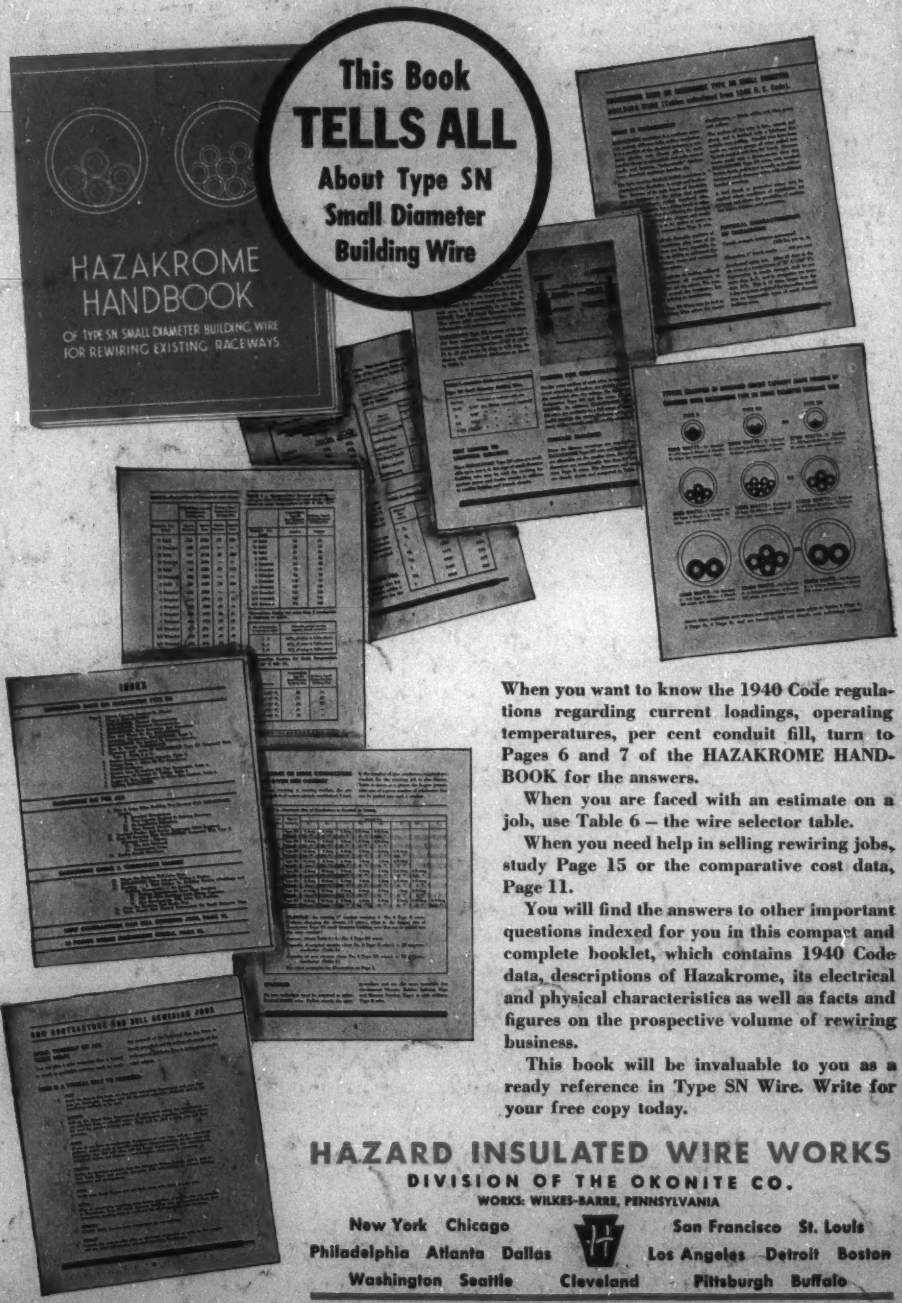

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